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Developments and breakthroughs in solar fuel production.

SFERA-III

Final Event

December 13, 2023 | Madrid, Spain

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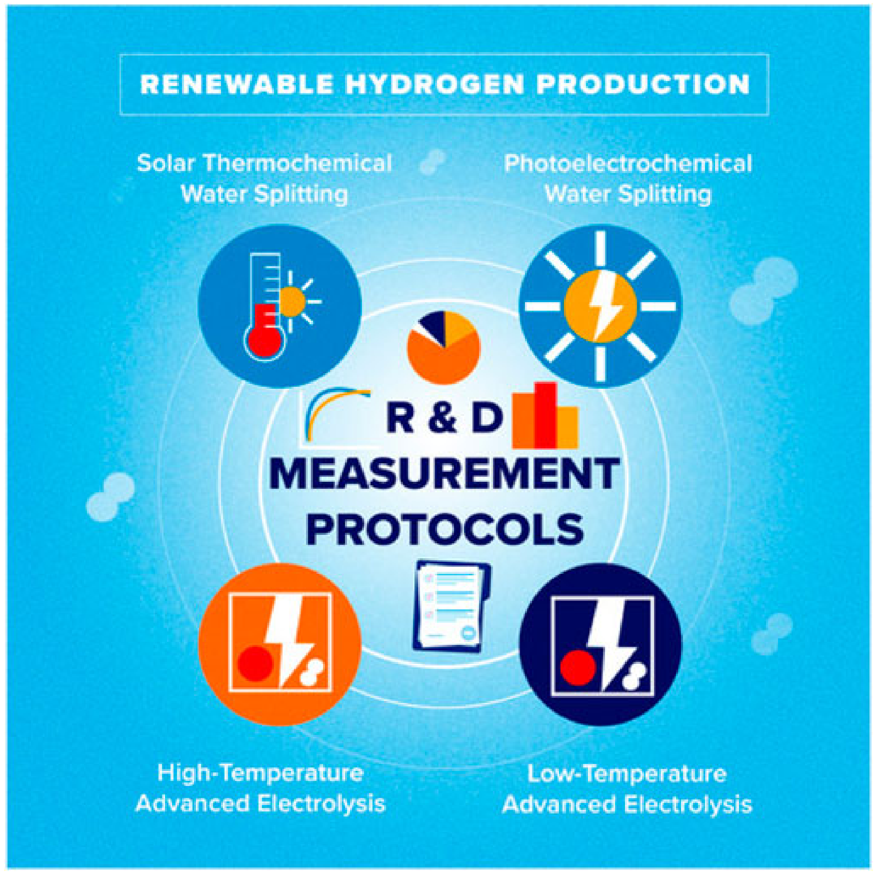
ETH Zurich (Now UCC Ireland)

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 823802

Key developments from SFERA III solar fuels research

- Formulation, dissemination, and application of performance indicators for solar fuel production reactors
- Demonstration of model based predictive control for solar biomass gasification
- Solar methane reforming at the solar tower in IMDEA
- Countercurrent regenerative reactors for enhanced chemical conversion

Performance indicators for solar fuel production reactors

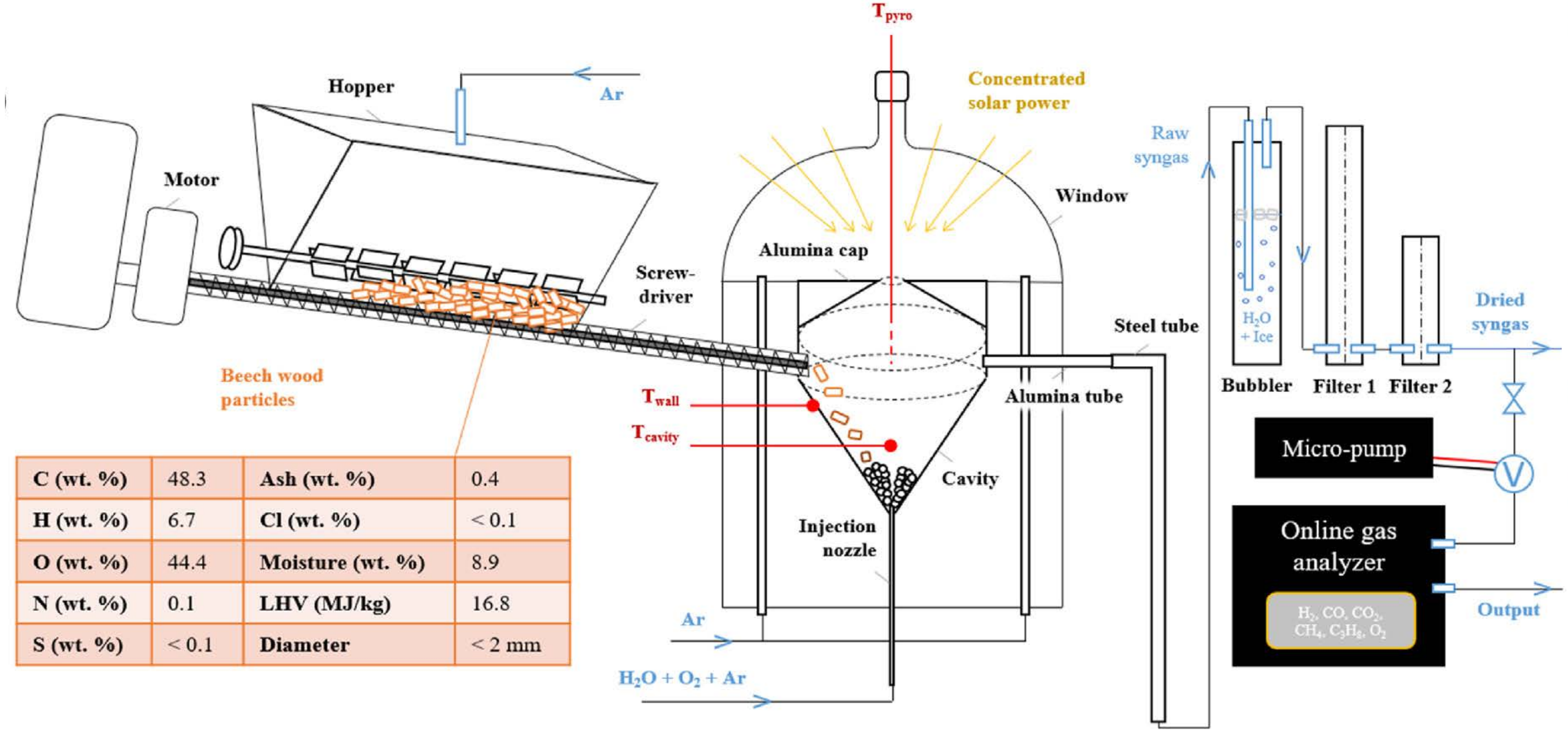


Frontiers in Energy Research
2023 Special Issue (DOE project HydroGEN): Advanced water splitting technologies development: Best practices and protocols.
Editors: Bulfin, Brendan, Marcelo Carmo, Roel Van de Krol, Julie Mougin, Kathy Ayers, Karl J. Gross, Olga A. Marina, George M. Roberts, Ellen B. Stechel
20 Articles

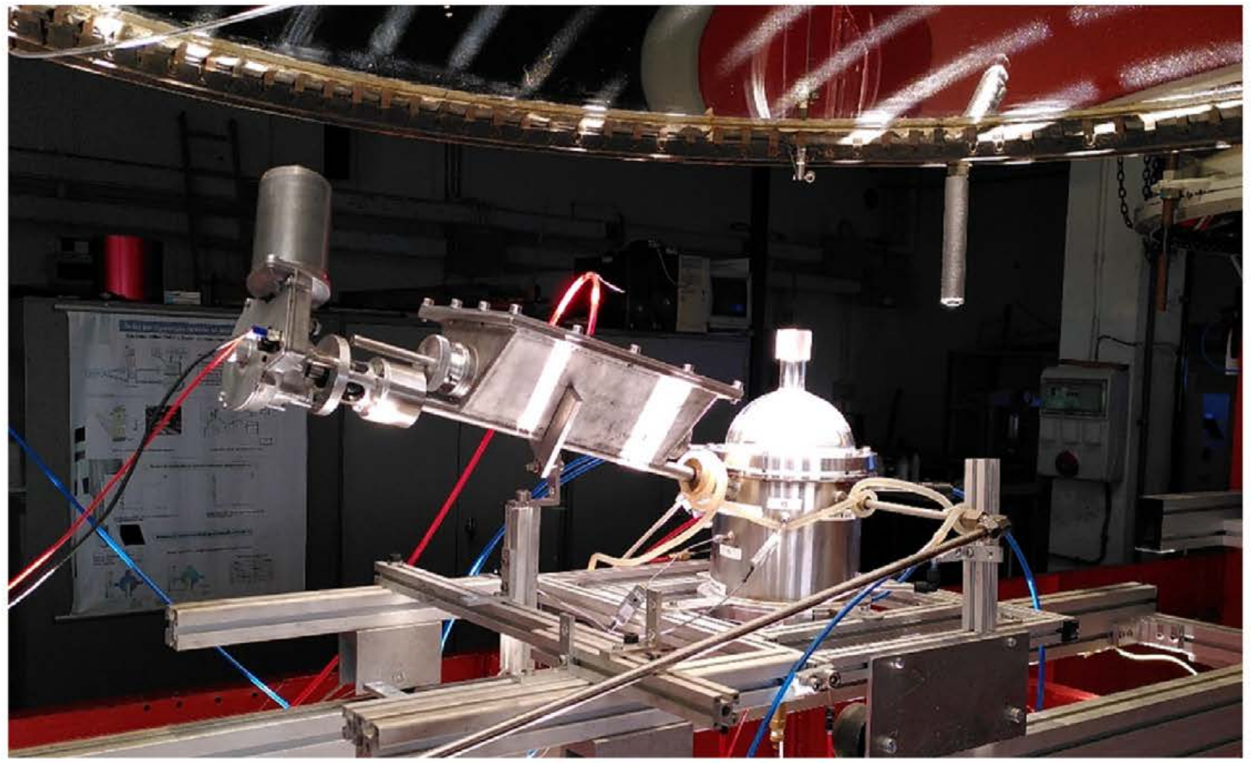
SFERA contribution (ETH & LNEG): Bulfin, B., Miranda, M., & Steinfeld, A. (2021). **Performance indicators for benchmarking solar thermochemical fuel processes and reactors.** *Frontiers in Energy Research*, *9*, 677980.
25 citations

Reactor type	Efficiency η	Conversion extent X_i	Selectivity (or Yield) S (or Y)
Thermochemical redox CO_2 splitting	$\frac{HHV_{CO}\int_0^{t_{cycle}} \dot{n}_{CO}(t)dt}{\int_0^{t_{cycle}} \dot{Q}(t)+\dot{Q}_{aux}(t)dt}$	$1-\frac{\int_0^{t_{cycle}} \dot{n}_{CO_2,f}dt}{\int_0^{t_{cycle}} \dot{n}_{CO_2,0}dt}$	$\frac{\int_0^{t_{cycle}} \dot{n}_{CO,f}dt}{\int_0^{t_{cycle}} \dot{n}_{CO_2,0}-\dot{n}_{CO_2,f}dt}$
Solar methane reforming	$\frac{\sum_i^{products} \dot{n}_i HHV_i}{\dot{Q}+\dot{n}_{CH_4,0}HHV_{CH_4}}$	$1-\frac{\dot{n}_{CH_4,f}}{\dot{n}_{CH_4,0}}$	$\frac{\dot{n}_{CO,f}}{\dot{n}_{CH_4,0}-\dot{n}_{CH_4,f}}$
Biomass gasification	$\frac{\sum_i^{prod} \dot{m}_i HHV_i}{\dot{Q}+\dot{m}_{biomass} HHV_{biomass}}$	$1-\frac{\dot{m}_{C-residue}}{\dot{m}_{C,0}}$	$\left(Y_{syngas}=\frac{\sum_i^{gases} \nu_{i,C}\dot{n}_{i,gas}}{\dot{n}_{C,0}}\right)$
Generic **A → B**	$\frac{\dot{n}_B HHV_B}{\dot{Q}+\dot{Q}_{aux}+\dot{n}_A HHV_A}$	$1-\frac{\dot{n}_{A,f}}{\dot{n}_{A,0}}$	$\frac{\dot{n}_{B,f}}{\dot{n}_{A,0}-\dot{n}_{A,f}}$

Solar biomass gasification (CEA & CNRS)



C (wt. %)	48.3	Ash (wt. %)	0.4
H (wt. %)	6.7	Cl (wt. %)	< 0.1
O (wt. %)	44.4	Moisture (wt. %)	8.9
N (wt. %)	0.1	LHV (MJ/kg)	16.8
S (wt. %)	< 0.1	Diameter	< 2 mm



Karout, Youssef, et al. "Model-based predictive control of a solar hybrid thermochemical reactor for high-temperature steam gasification of biomass." *Clean Technologies* 5.1 (2023): 329-351.

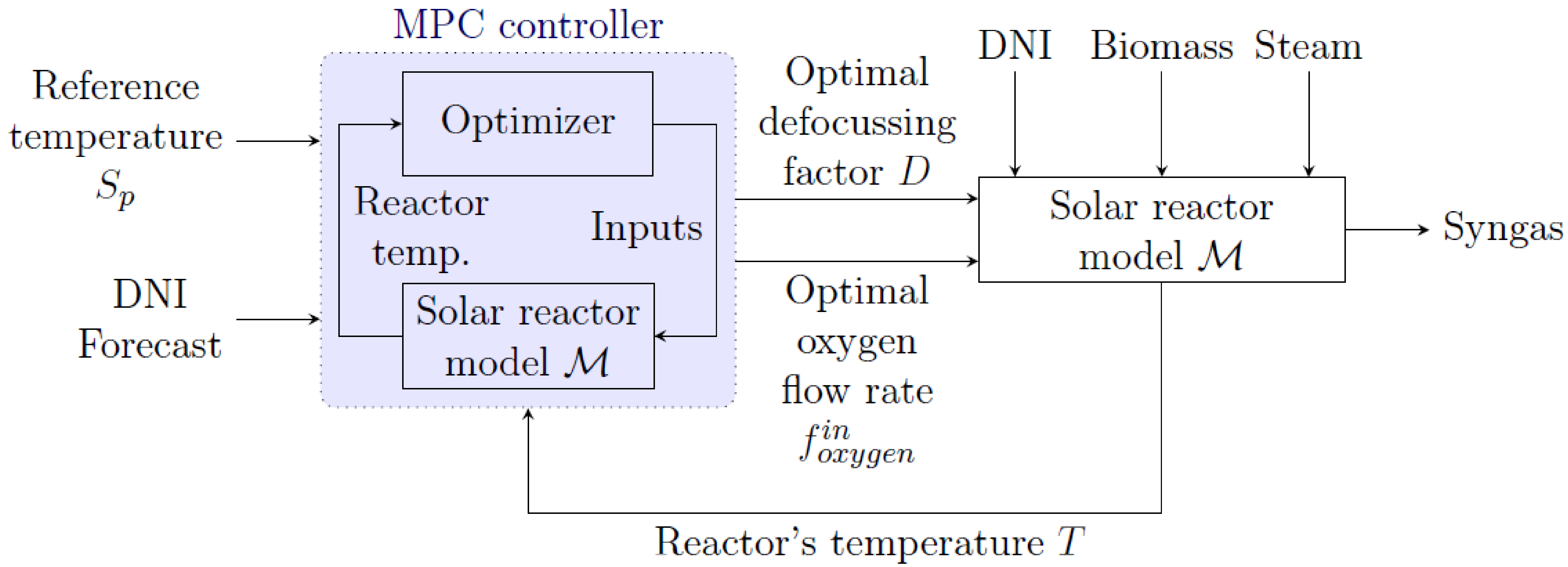
Curcio, Axel, et al. "Design and validation of reactant feeding control strategies for the solar-autothermal hybrid gasification of woody biomass." *Energy* 254 (2022): 124481.

Zuber, Mario, et al. "Methane dry reforming via a ceria-based redox cycle in a concentrating solar tower." *Sustainable Energy & Fuels* 7.8 (2023): 1804-1817.

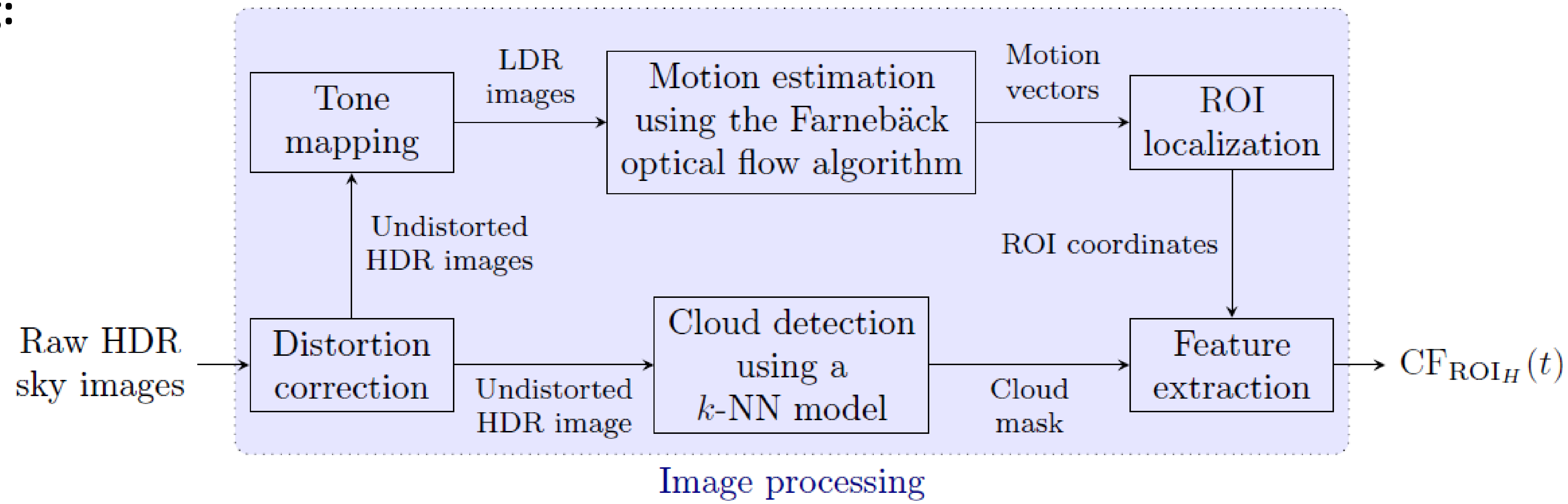
Curcio, Axel, et al. "Experimental assessment of woody biomass gasification in a hybridized solar powered reactor featuring direct and indirect heating modes." *International Journal of Hydrogen Energy* 46.75 (2021): 37192-37207.

Solar biomass gasification - automation

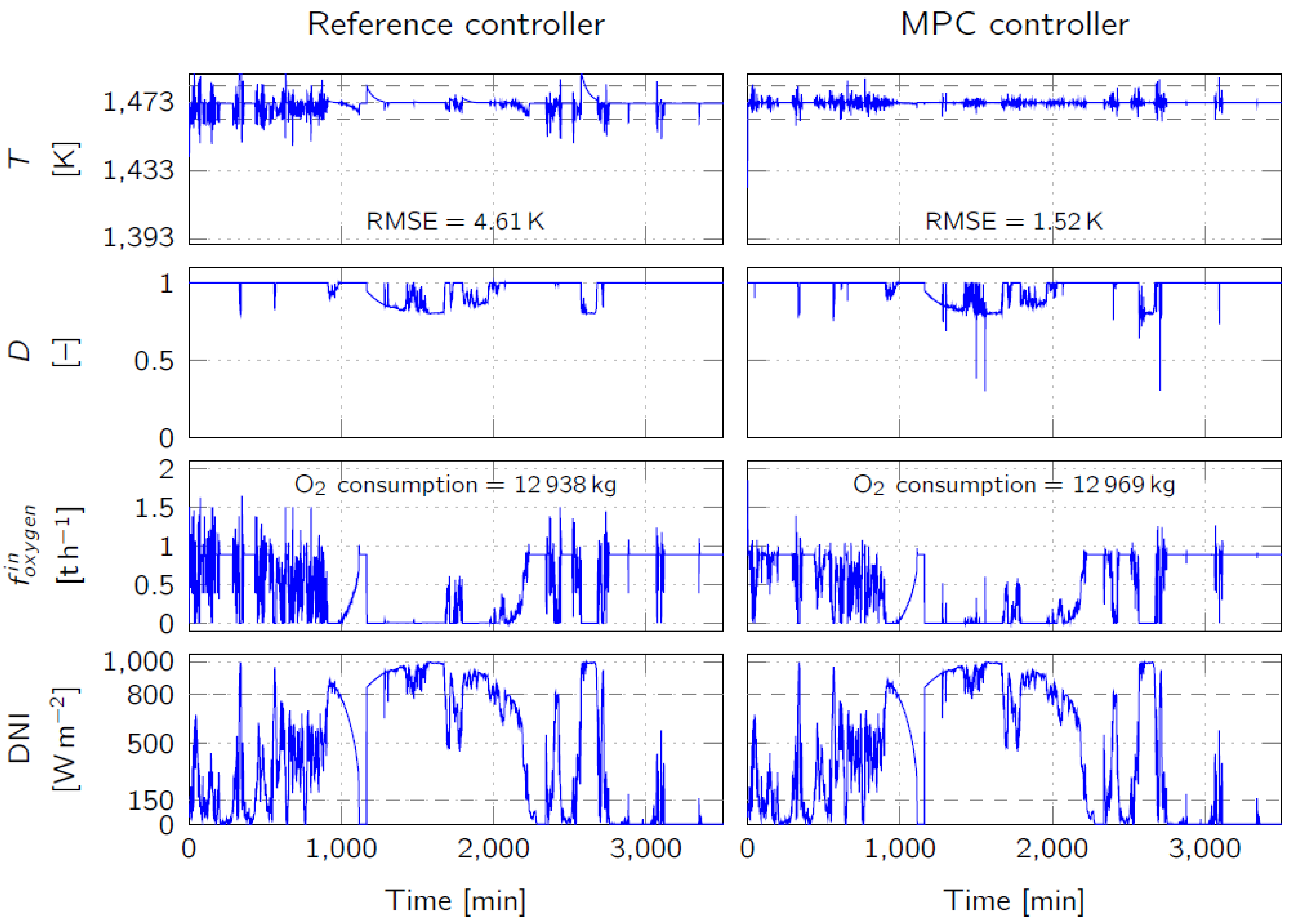
Reactor Control:



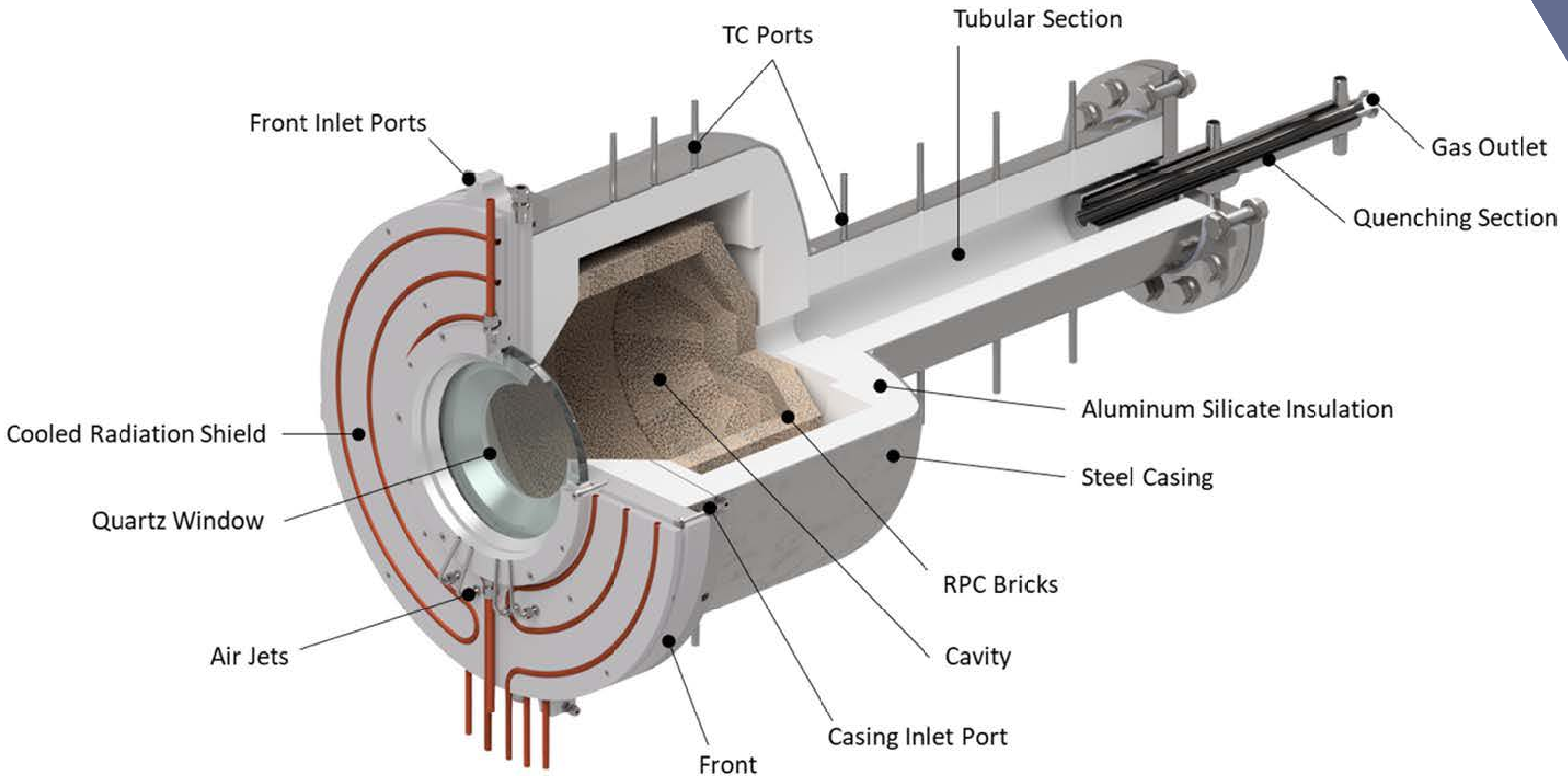
DNI Forecasting:



Solar biomass gasification – automation testing

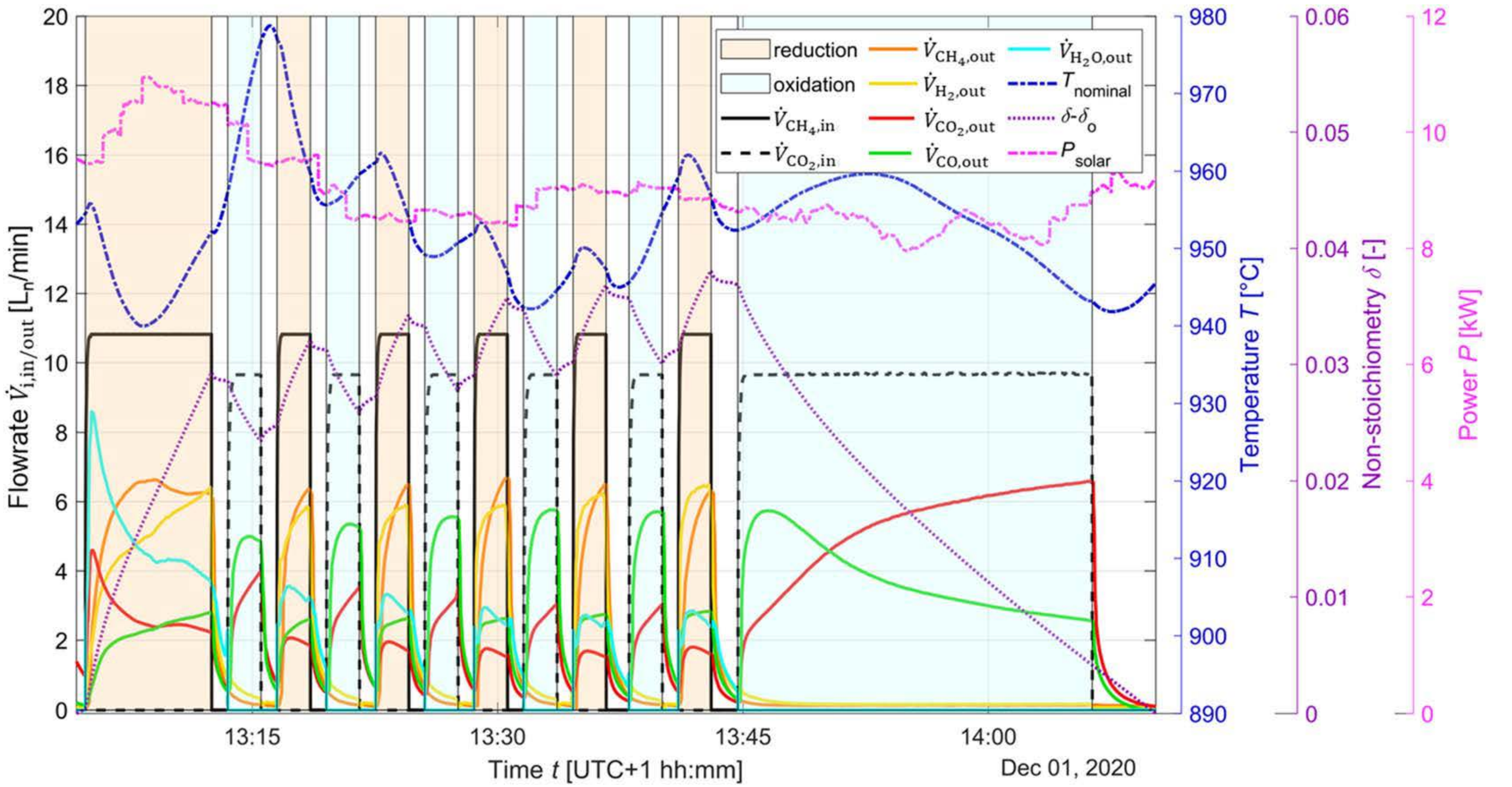


Solar methane reforming (ETHZ & IMDEA)

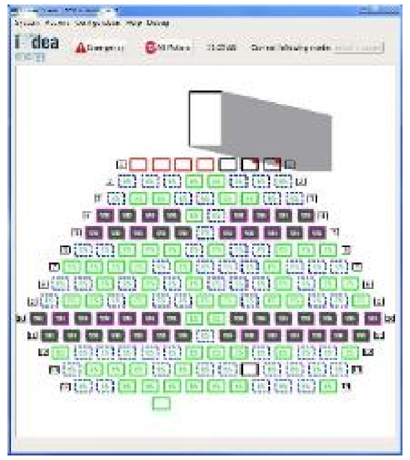


Zuber, Mario, et al. "Methane dry reforming via a ceria-based redox cycle in a concentrating solar tower." *Sustainable Energy & Fuels* 7.8 (2023): 1804-1817.

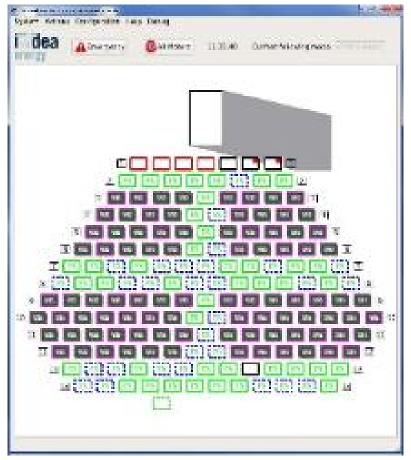
Solar methane reforming – Heliostat control (SCADA)



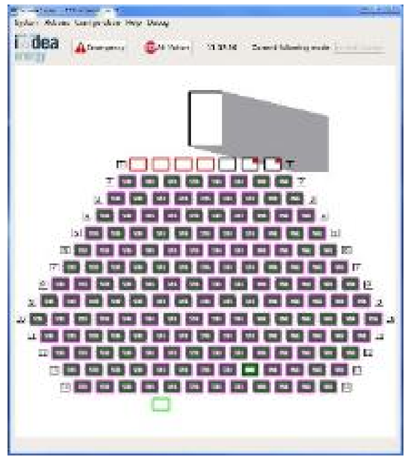
Preheating (9:39)
Solar reactor



Preheating (10:00)
Solar reactor



Cycle 1 (12:25)
Solar reactor



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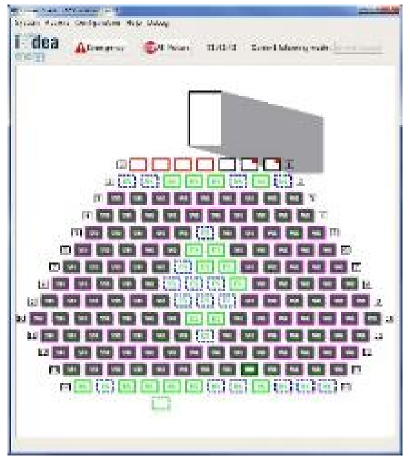
Cycle 4 (12:25)
Solar reactor



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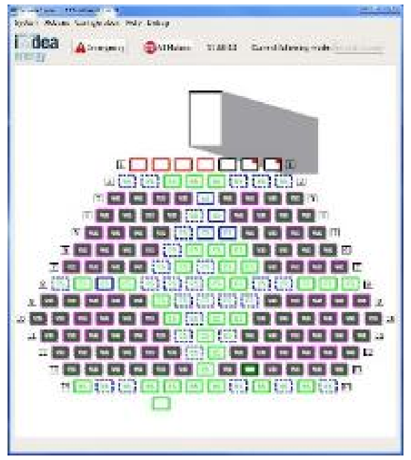
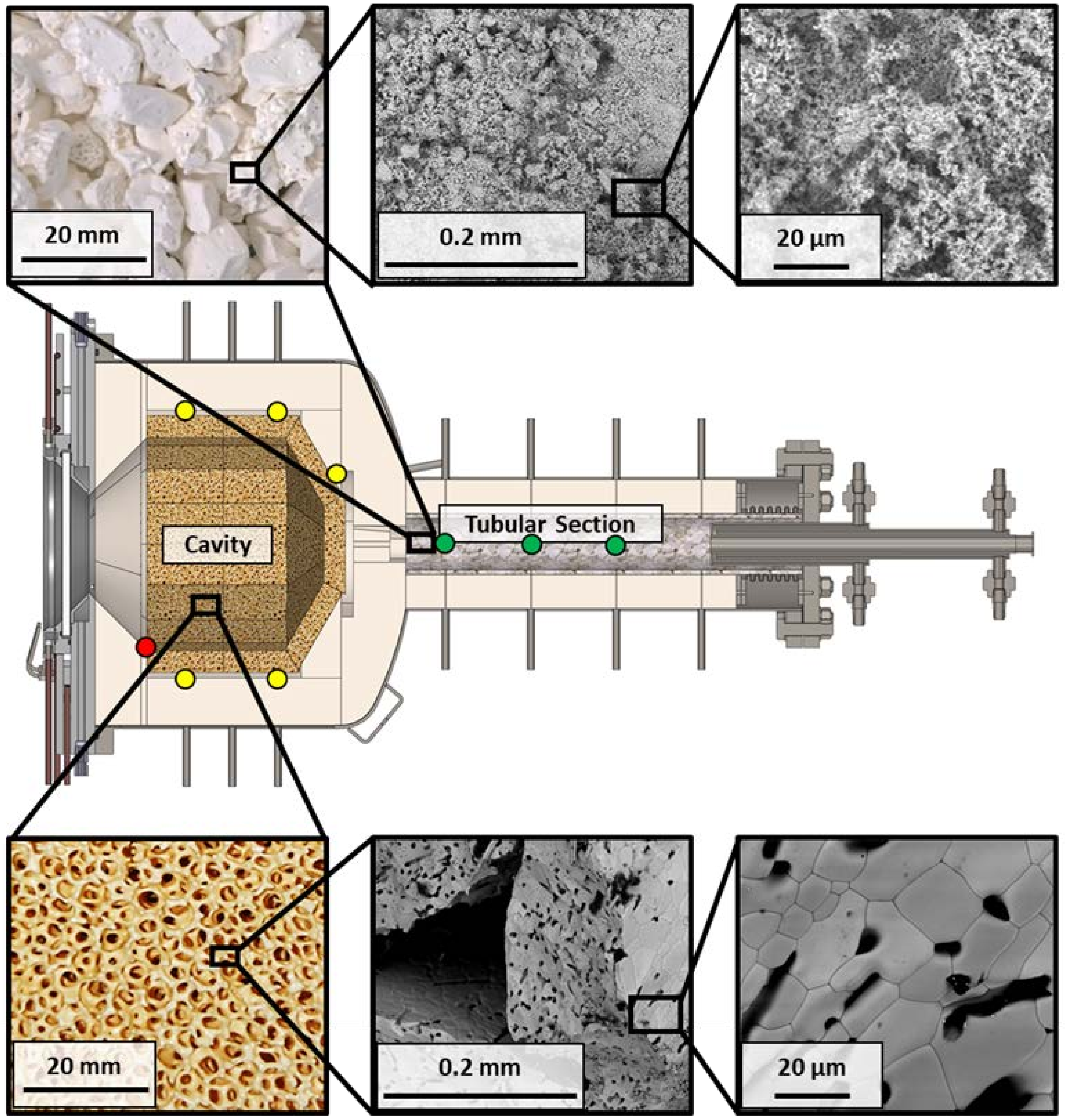
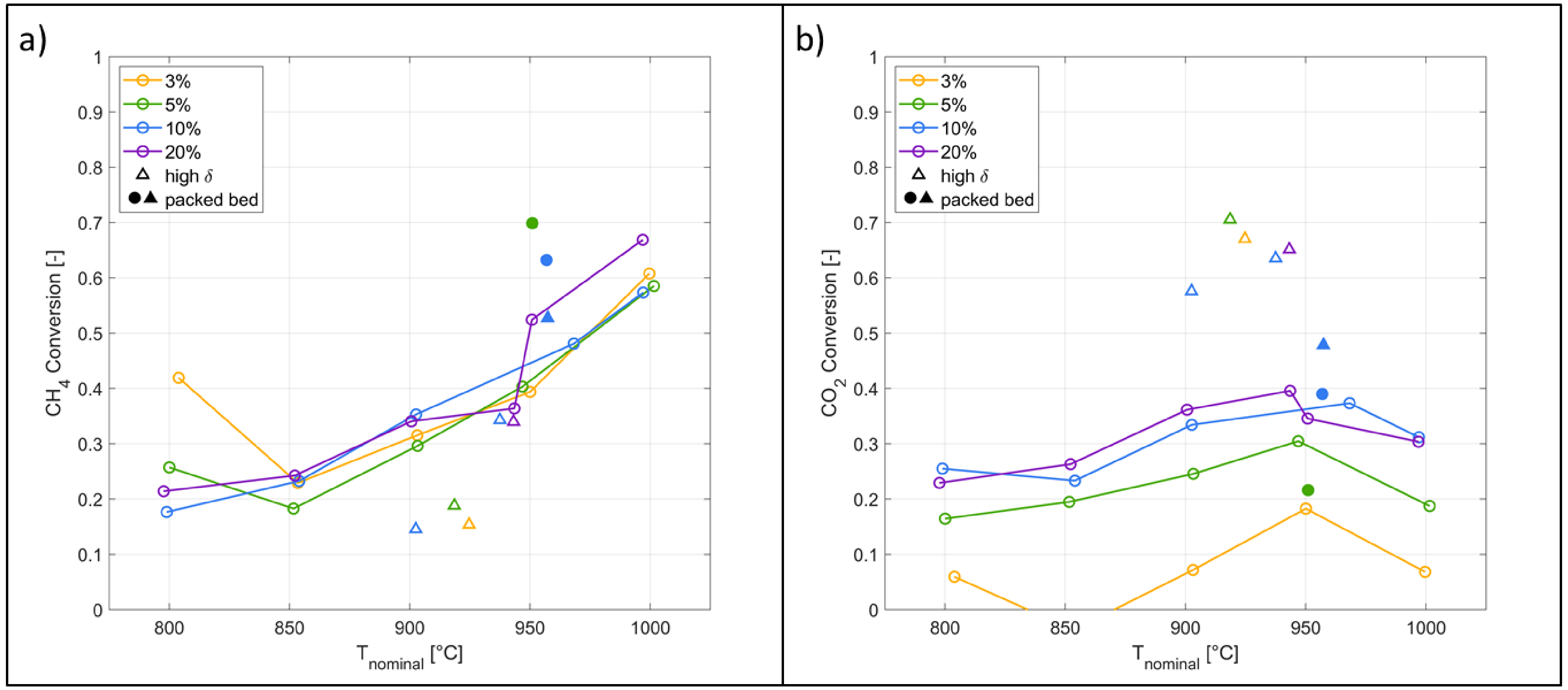
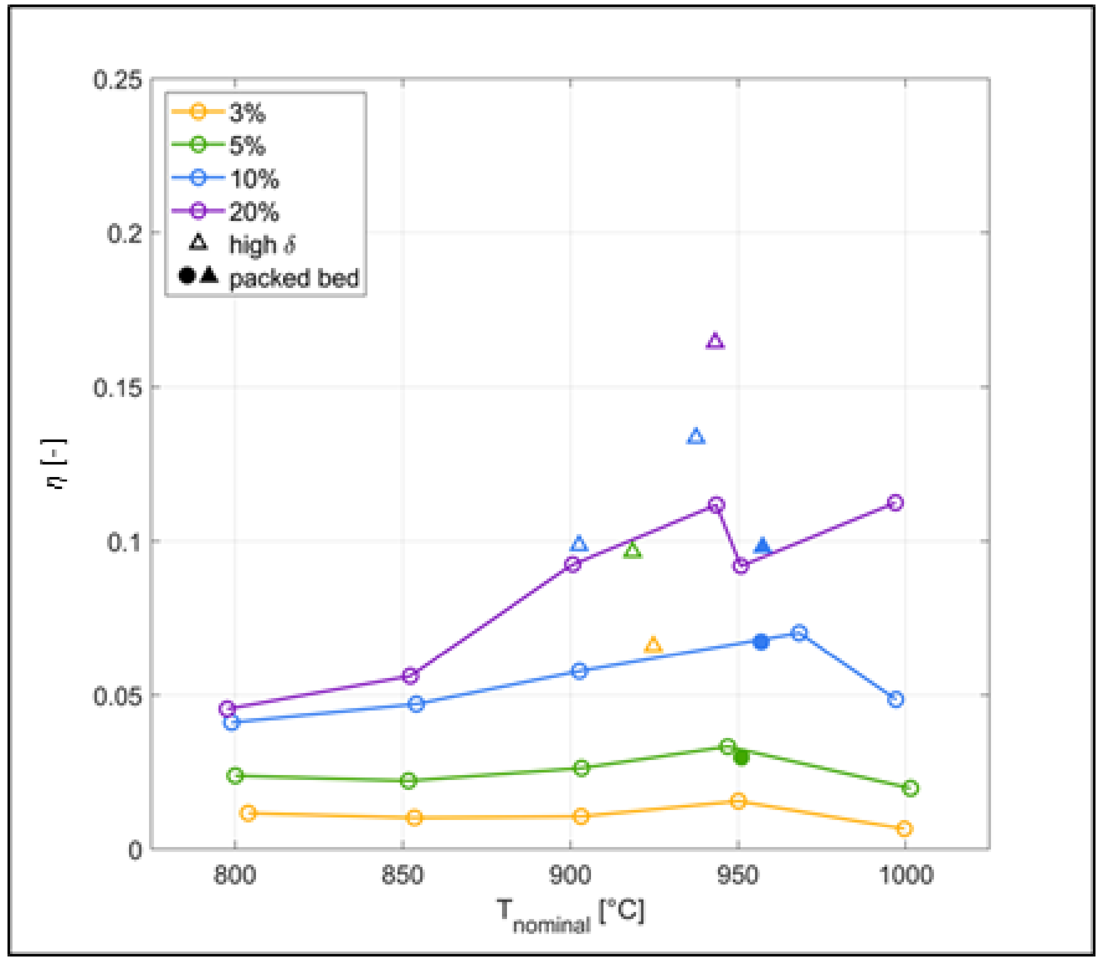
Cycle 7 (13:57)
Solar reactor



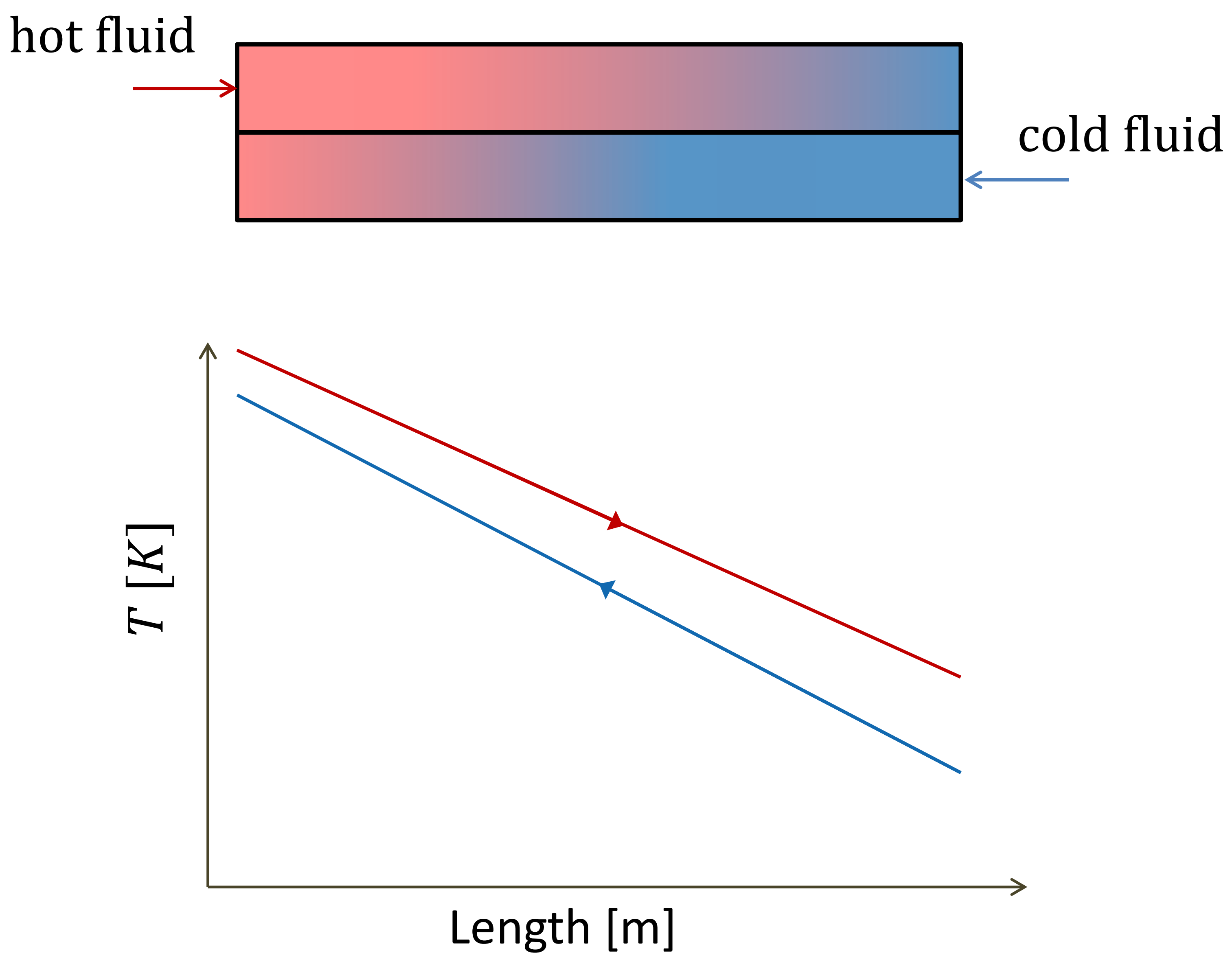
Solar methane reforming – Reactor Performance



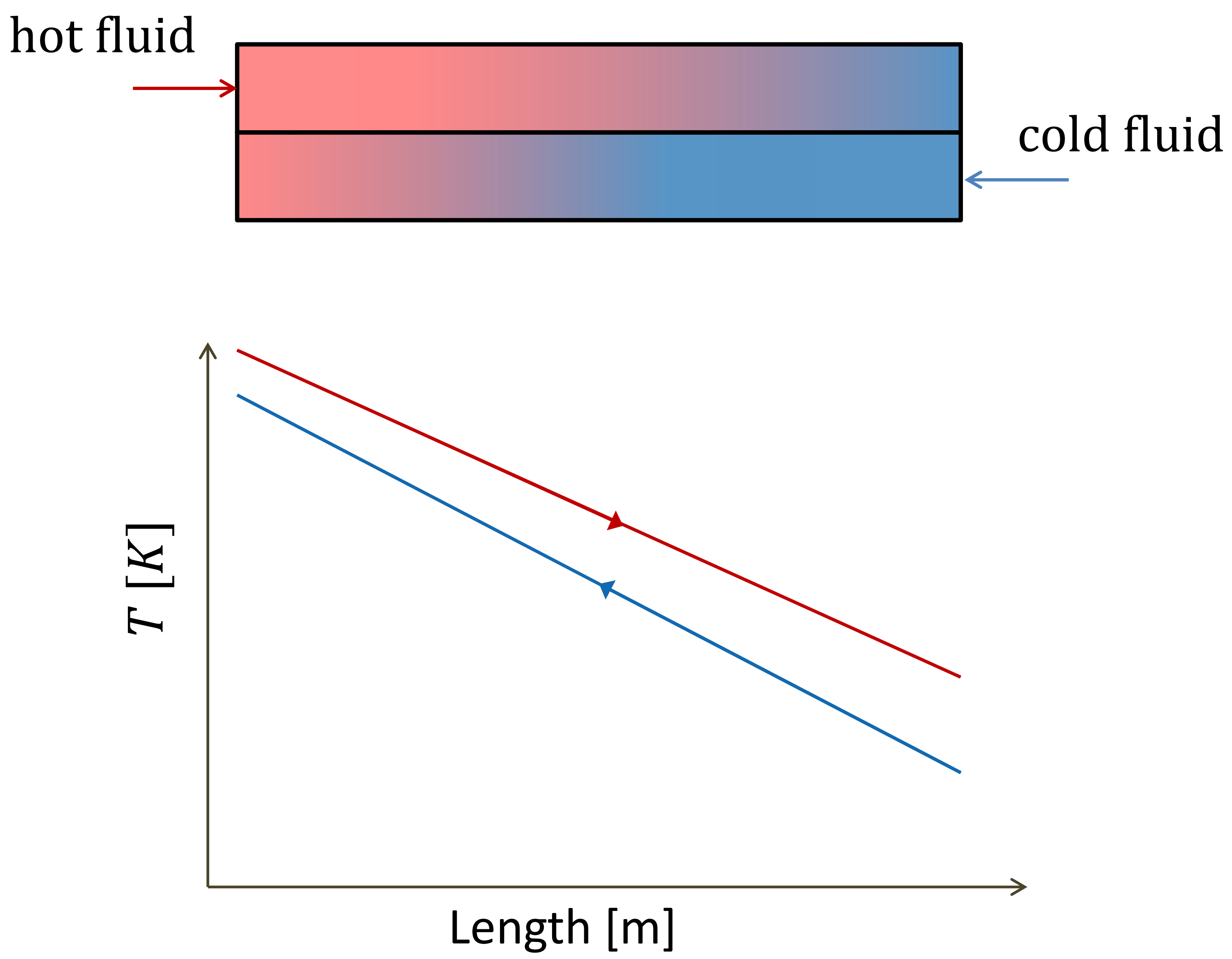




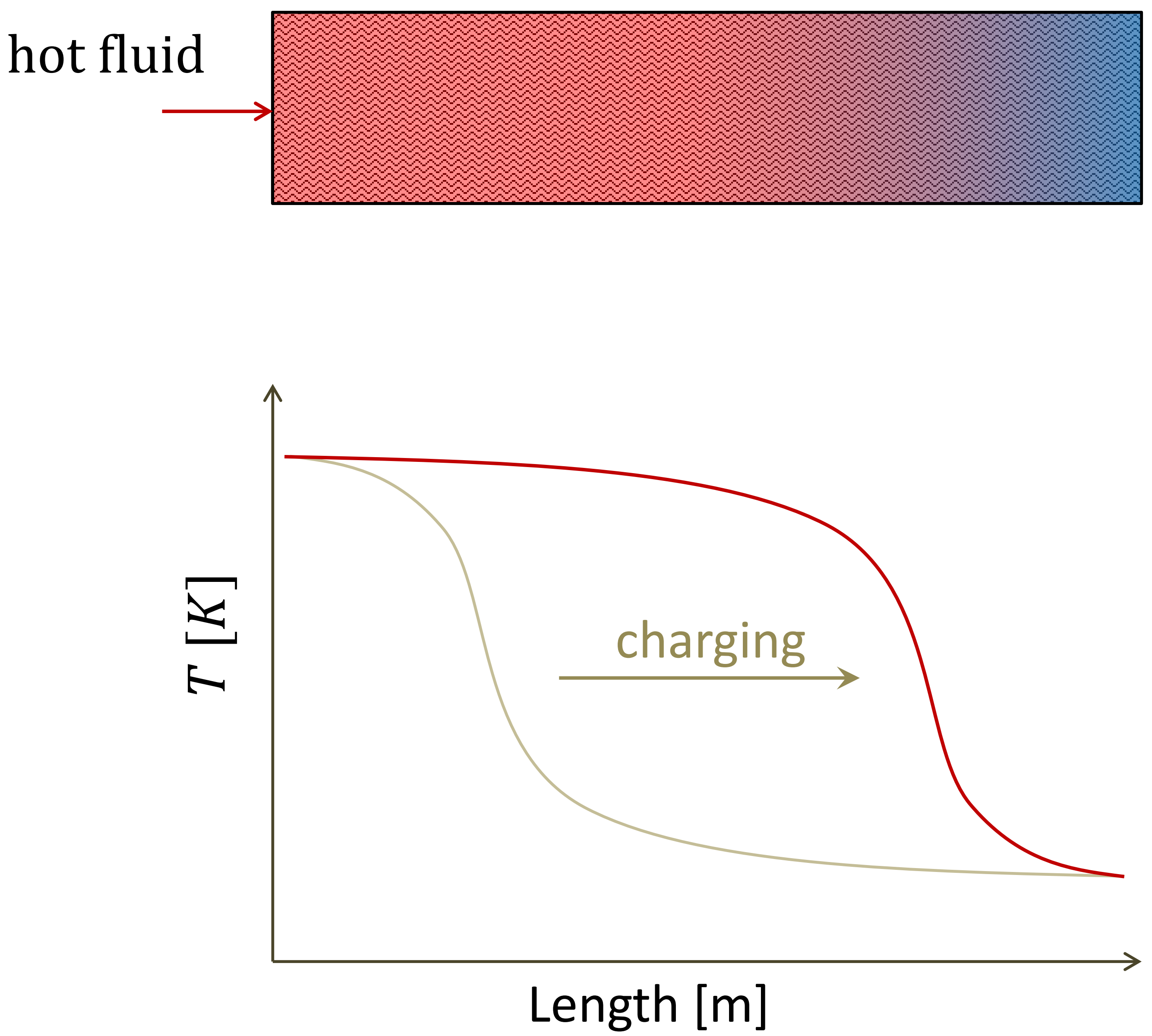
Countercurrent heat exchangers



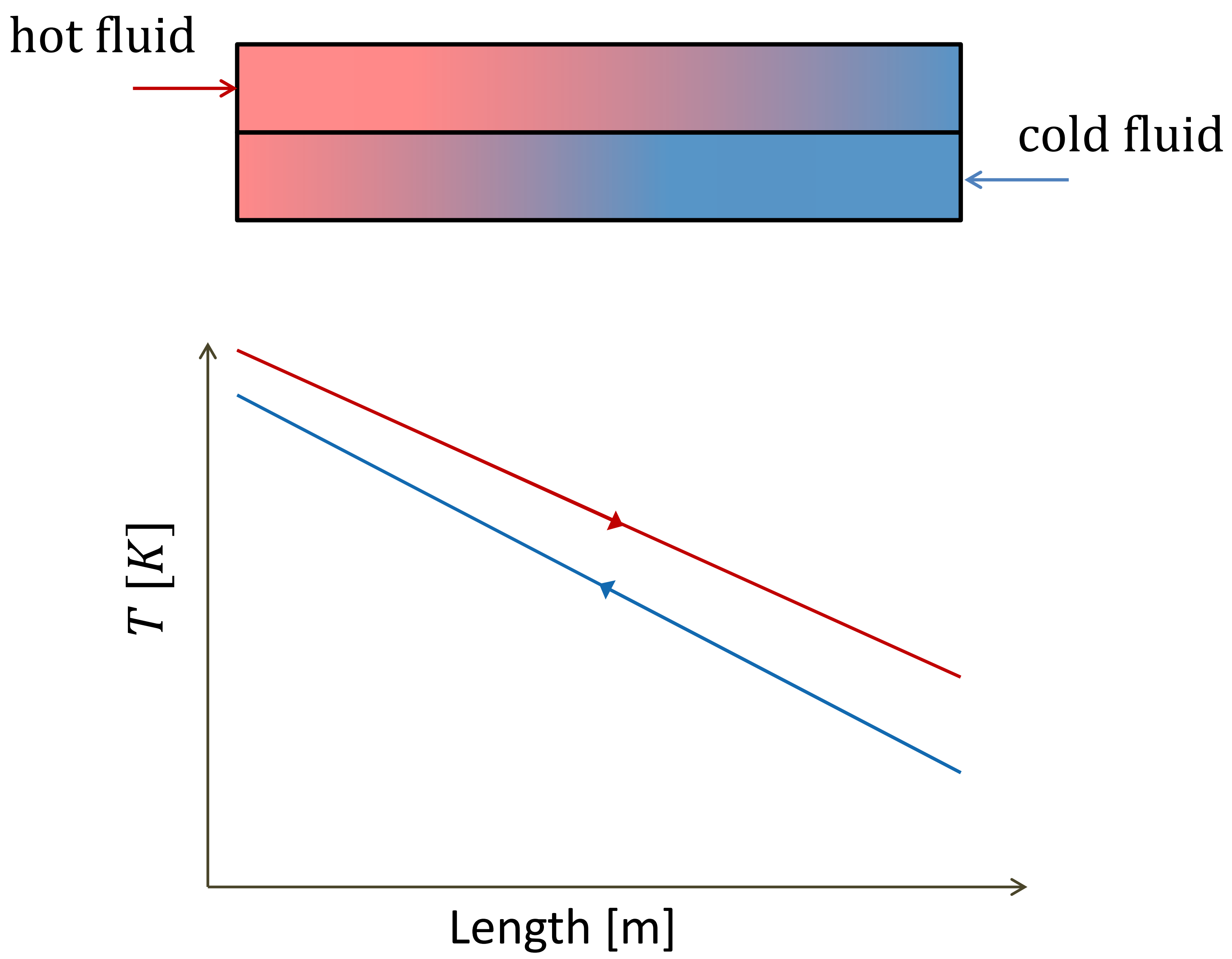
Countercurrent heat exchangers

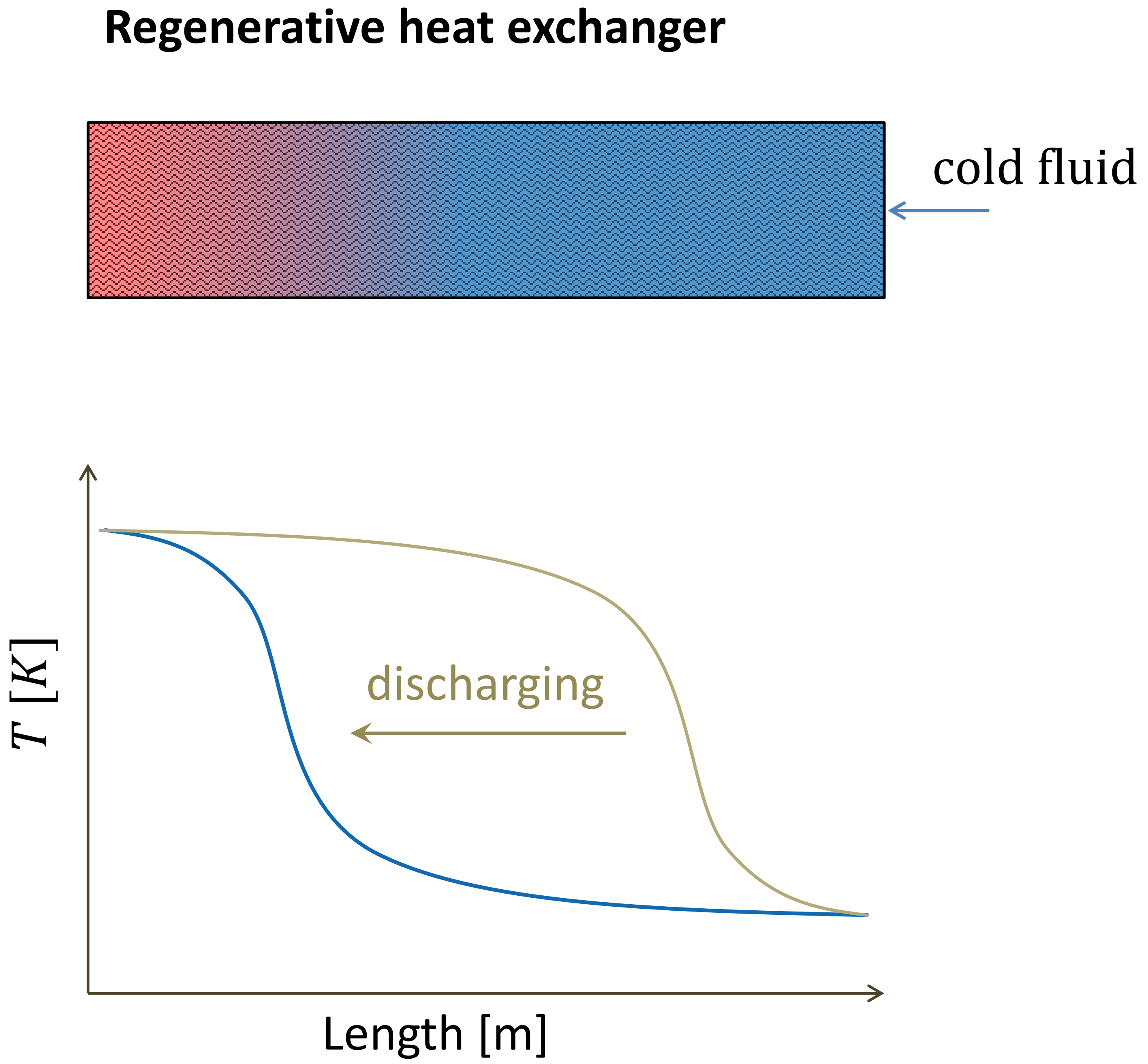


Regenerative heat exchanger



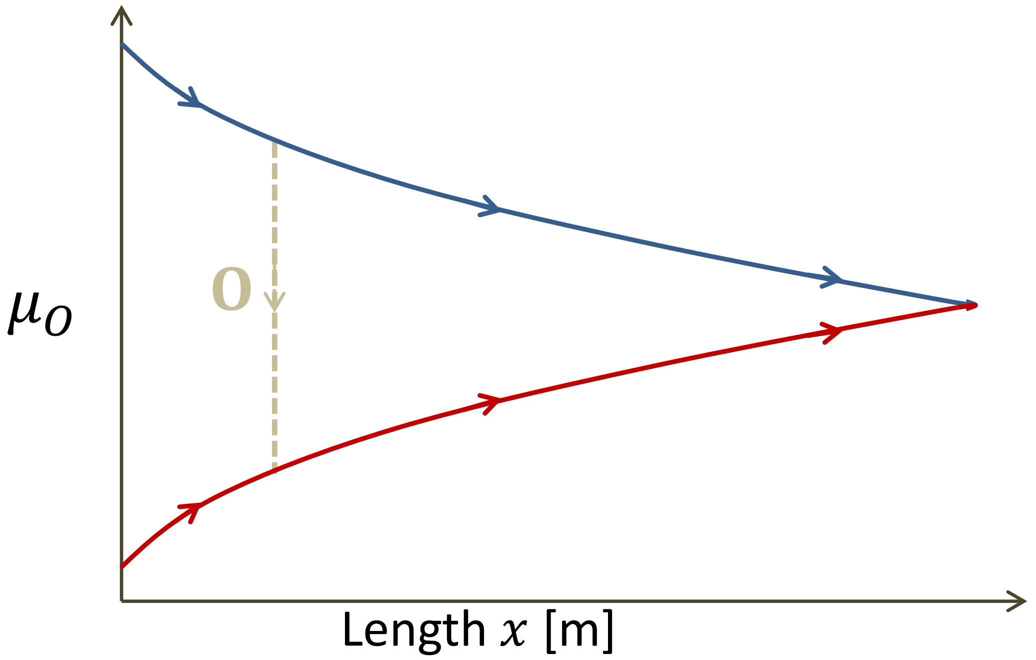
Countercurrent heat exchangers

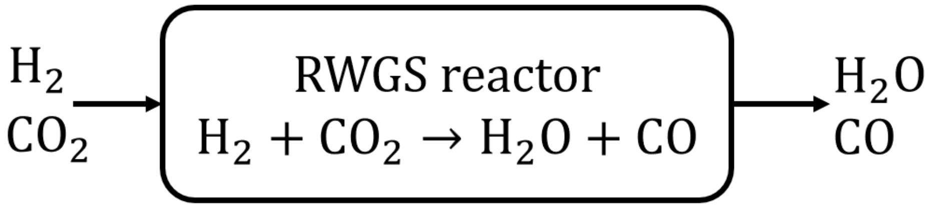




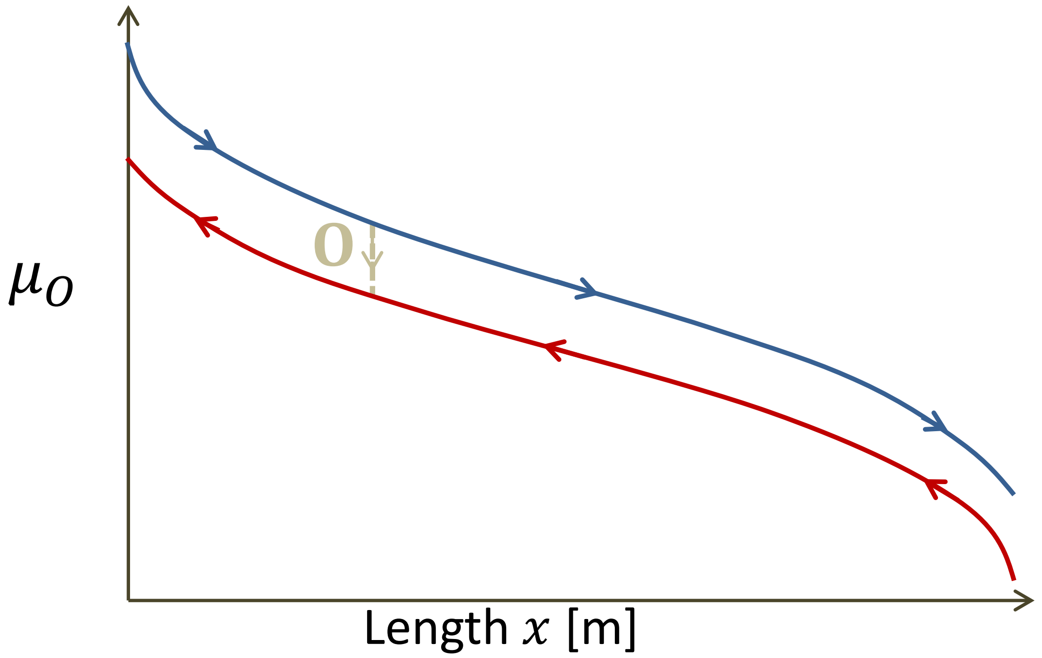
Countercurrent reactors – same principle

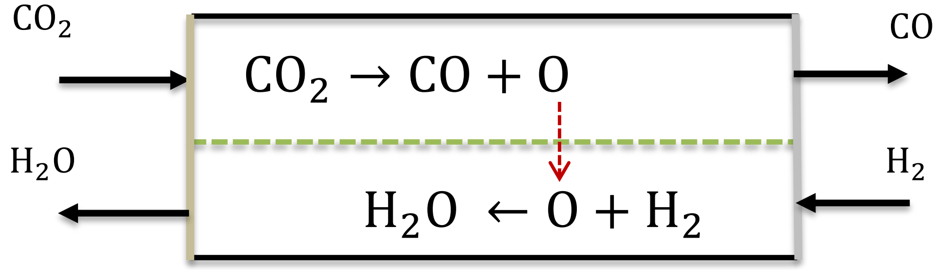
Cocurrent oxygen exchange reactor



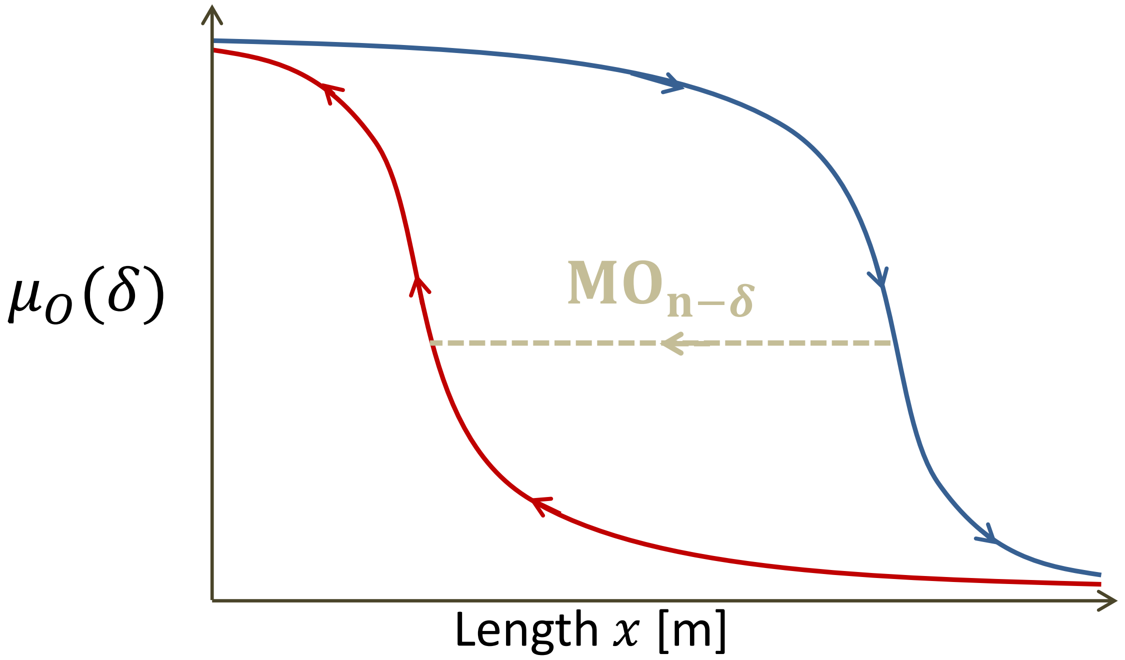


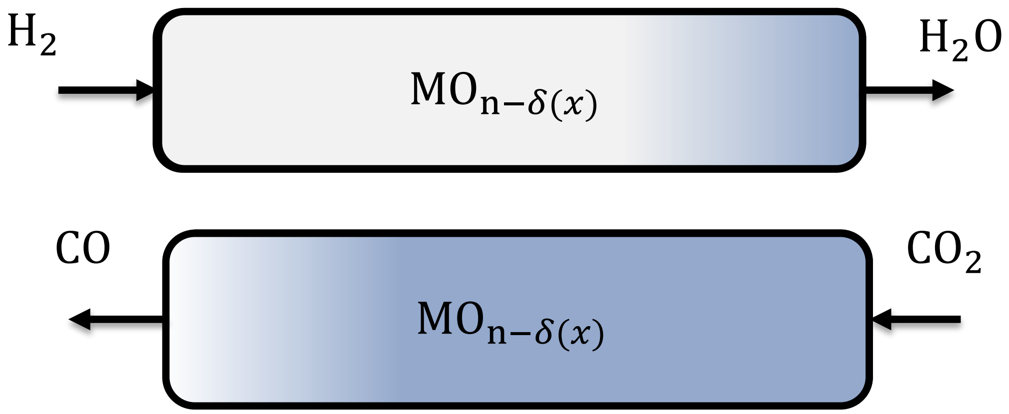
Countercurrent oxygen exchange reactor



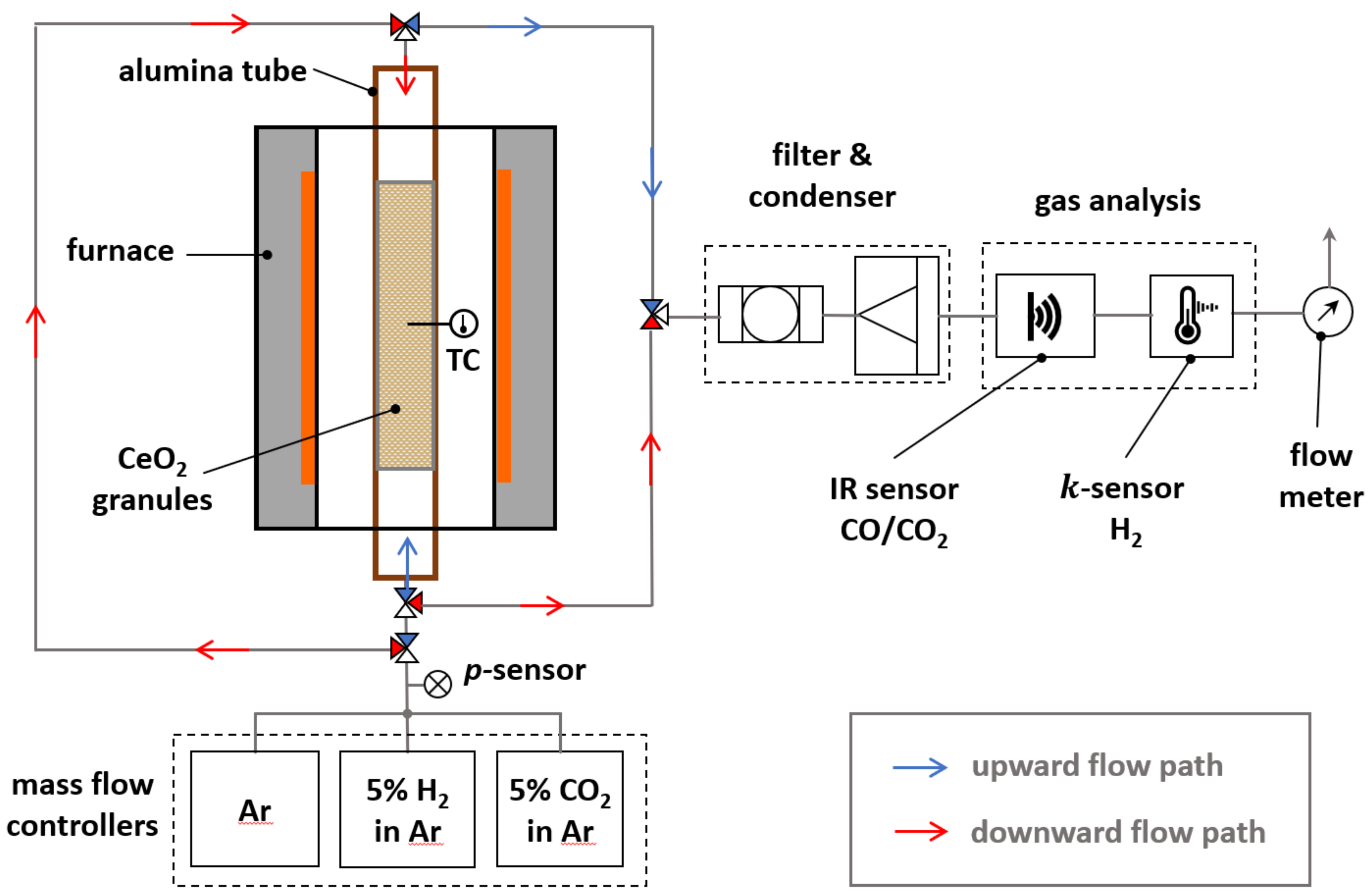


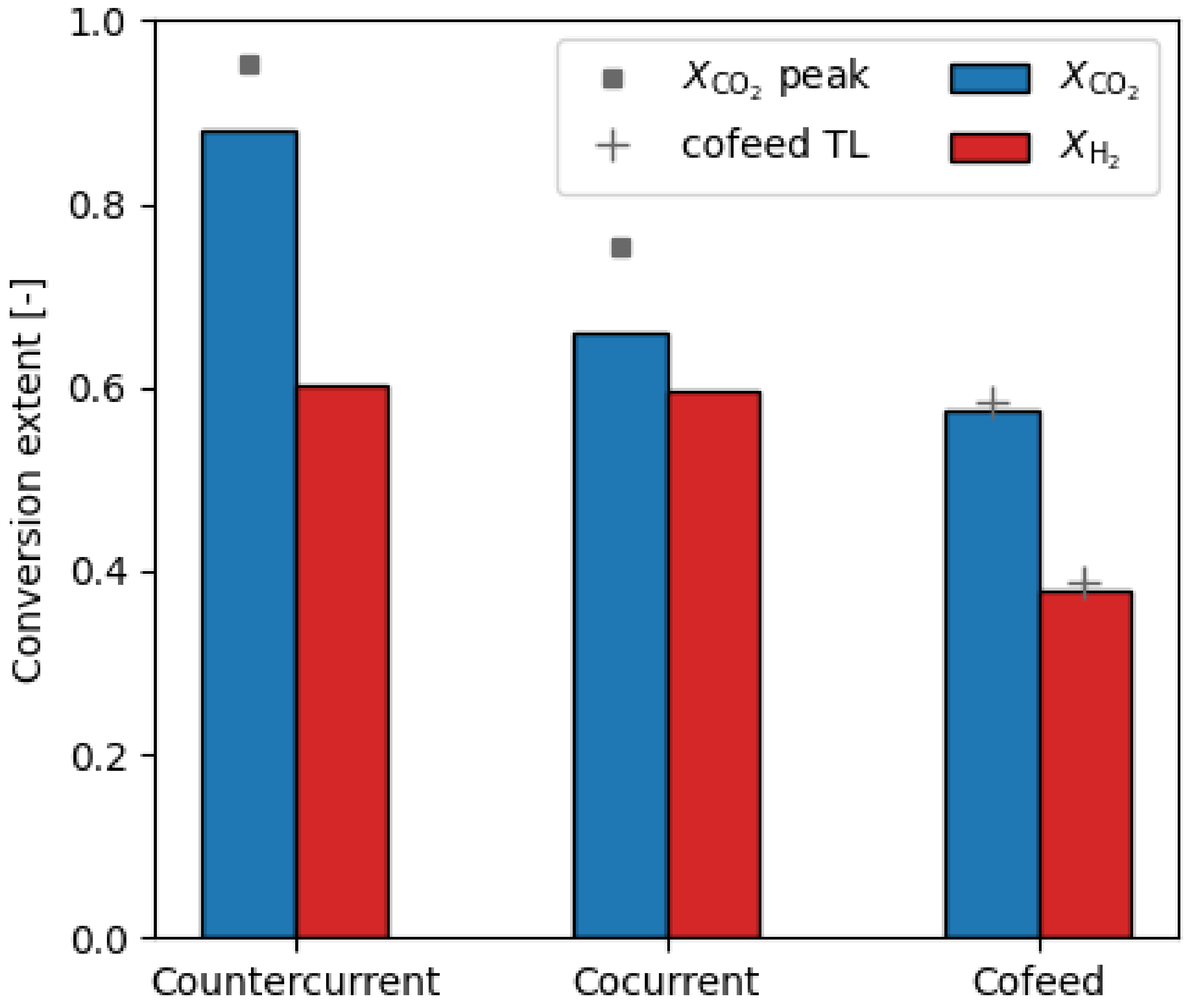
Countercurrent regenerative reactor





Countercurrent regenerative reactor – Demonstration

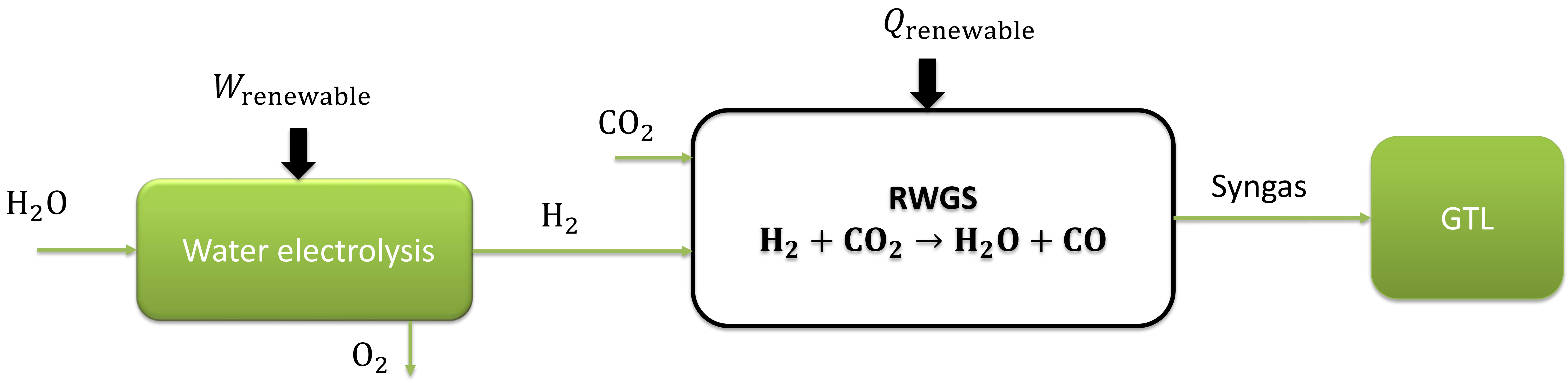




Bulfin, B., Zuber, M., Gräub, O., & Steinfeld, A. (2023). Intensification of the reverse water–gas shift process using a countercurrent chemical looping regenerative reactor. *Chemical Engineering Journal*, *461*, 141896.

Countercurrent regenerative reactor – application

Power-to-X and the RWGS reaction



Follow on investigations

- *Automation of scaled up solar reactors*
  - *Heliostat control, DNI forecasting, model based predictive control, demonstrating TRL 5 +*

- Follow up research on solar fuel reactor systems:
  - ***Biomass gasification*** *- scale up and on un sun testing*
  - ***Methane reforming –*** *Test direct catalytic route*
  - ***Two-step cycles –*** *Sun-to-liquid 2*
- Follow up research on regenerative reactor systems:
  - ***3 proposals submitted*** *(one failed)*
  - *Targeted applications are Power-to-X and methane reforming*

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Thank You

For Your Attention

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