UNIVERSITY OF CAMBRIDGE

Carbon capture and follow on work

Stuart Scott et al.

Engineering Department

Introduction

- **UKCCSRC Capture Theme**: focus on next generation CO_2 capture technologies and processes, including high and low temperature solids-based cycles, and links closely with the systems work.
- (i) solid sorbents and (ii) oxygen transfer materials for carbon capture
- Focussed on fixed bed processes, since they offer an interesting and industrially-relevant alternative to continuous fluidised beds.

Oxygen transfer materials

The oxygen transfer reaction used for chemical looping is characterised by the equilibrium for

$$Me(s) \ + \frac{1}{2} O_2 \rightleftharpoons MeO(\mathrm{s})$$

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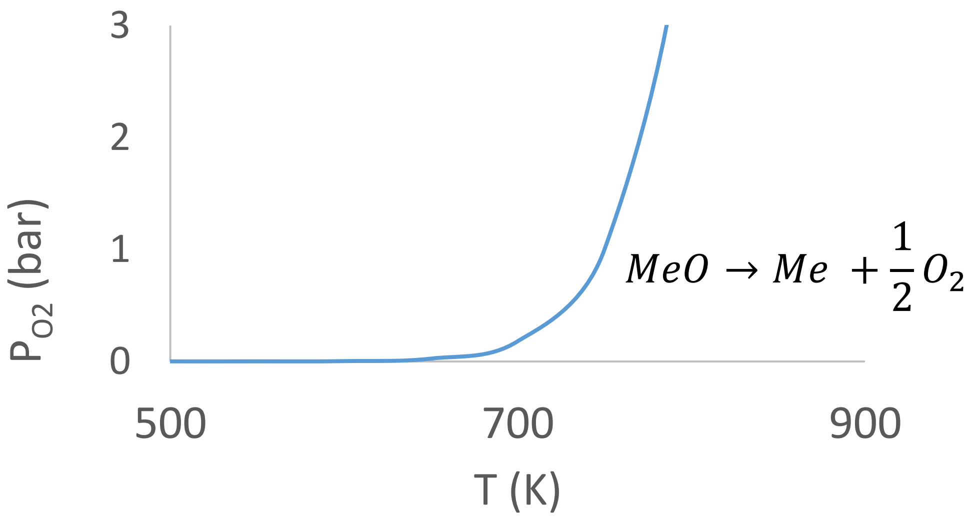
$$= e^{-\Delta H/RT} e^{\Delta S/R}$$



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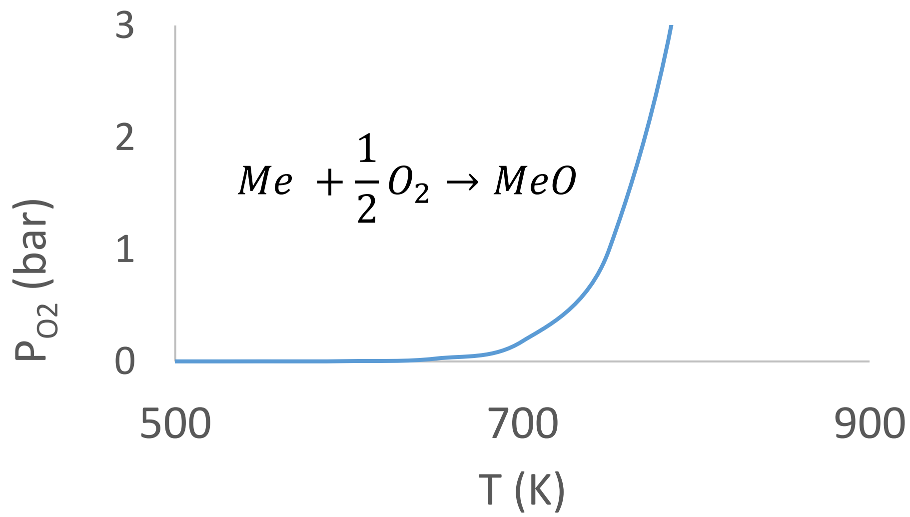


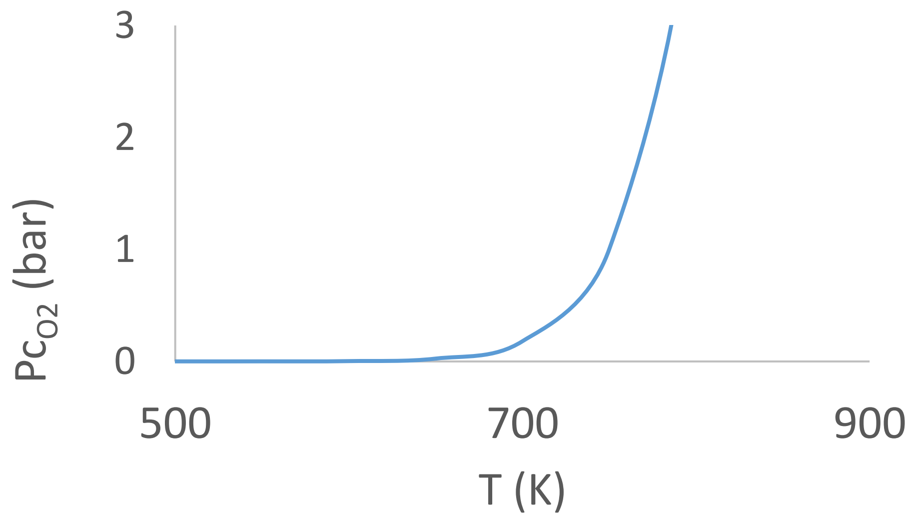
Carbon doxide transfer materials

The oxygen transfer reaction used for carbonate looping is characterised by the equilibrium for

$$MeO(s) + CO_2 \rightleftharpoons MeCO_3(\mathrm{s})$$

The equilibrium oxygen pressure is

$$P_{CO2} = e^{-\Delta G/RT} = e^{-\Delta H/RT} e^{\Delta S/R}$$



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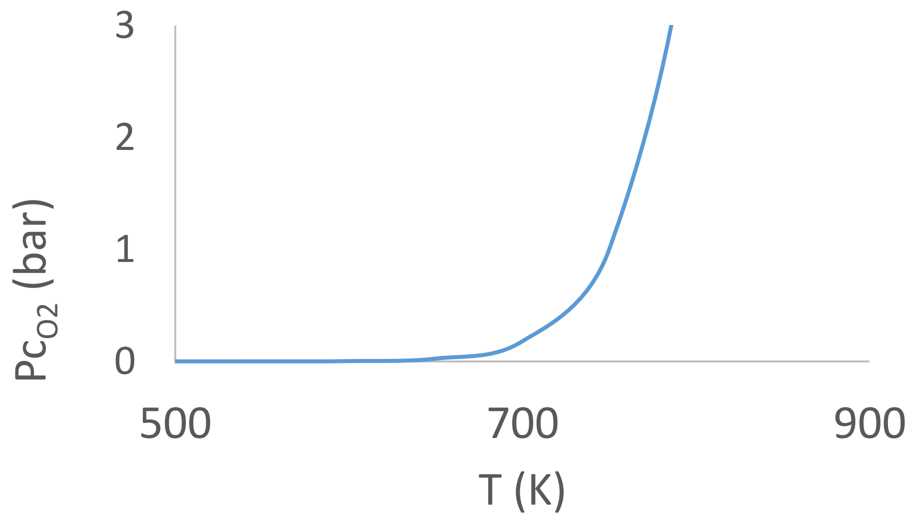

CO2 sorbents – e.g. 13X

The oxygen transfer reaction used for chemical looping is characterised by the equilibrium for

$$X\ (s) + \delta CO_2 \rightleftharpoons X(CO_2)_\delta\ \text{(s)}$$

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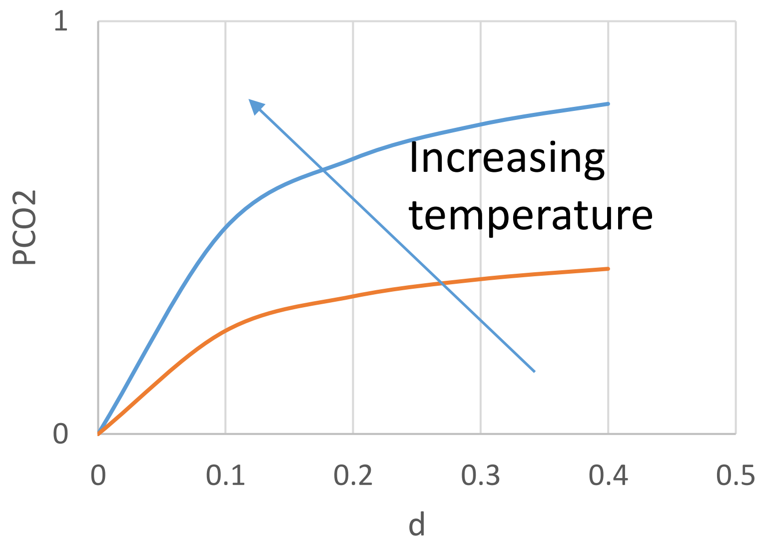
The equilibrium CO_2 pressure is

$$P_{CO_2} = fn(T, \delta)$$



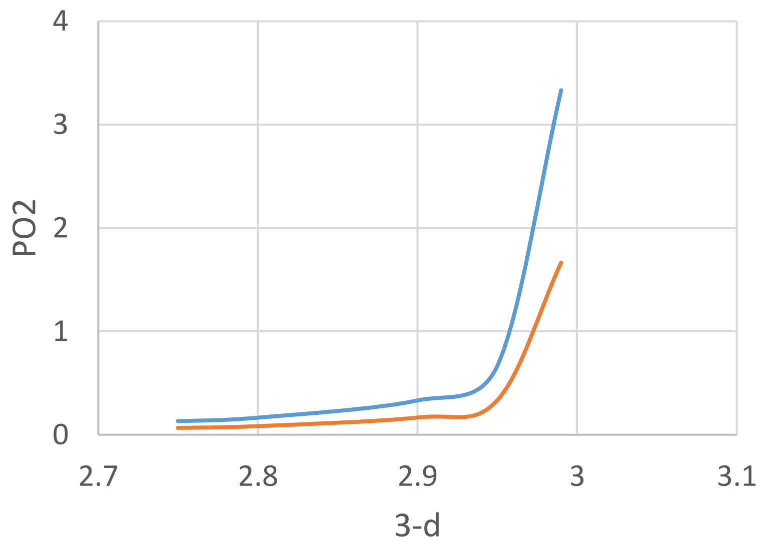
Non-stoichiometric Oxygen transfer materials

The oxygen transfer reaction used for chemical looping is characterised by the equilibrium for

$$MeO_{1-\delta}\,(s) + \frac{\delta}{2} O_2 \rightleftharpoons MeO(\mathrm{s})$$

The equilibrium oxygen pressure is

$$P_{O_2} = fn(T, \delta)$$



Examples: $SrFeO_{3-\delta}$

Governing equations in packed beds

Regardless of the system, sorbent or oxygen carrier, the underlying equations and rate expressions are the same

Gas balances: $$\epsilon \frac{\partial C_i}{\partial t} = -\frac{\partial}{\partial z}\left(\rho u \epsilon y_i - D_{ax} C_t \frac{\partial y_i}{\partial z}\right) + r$$

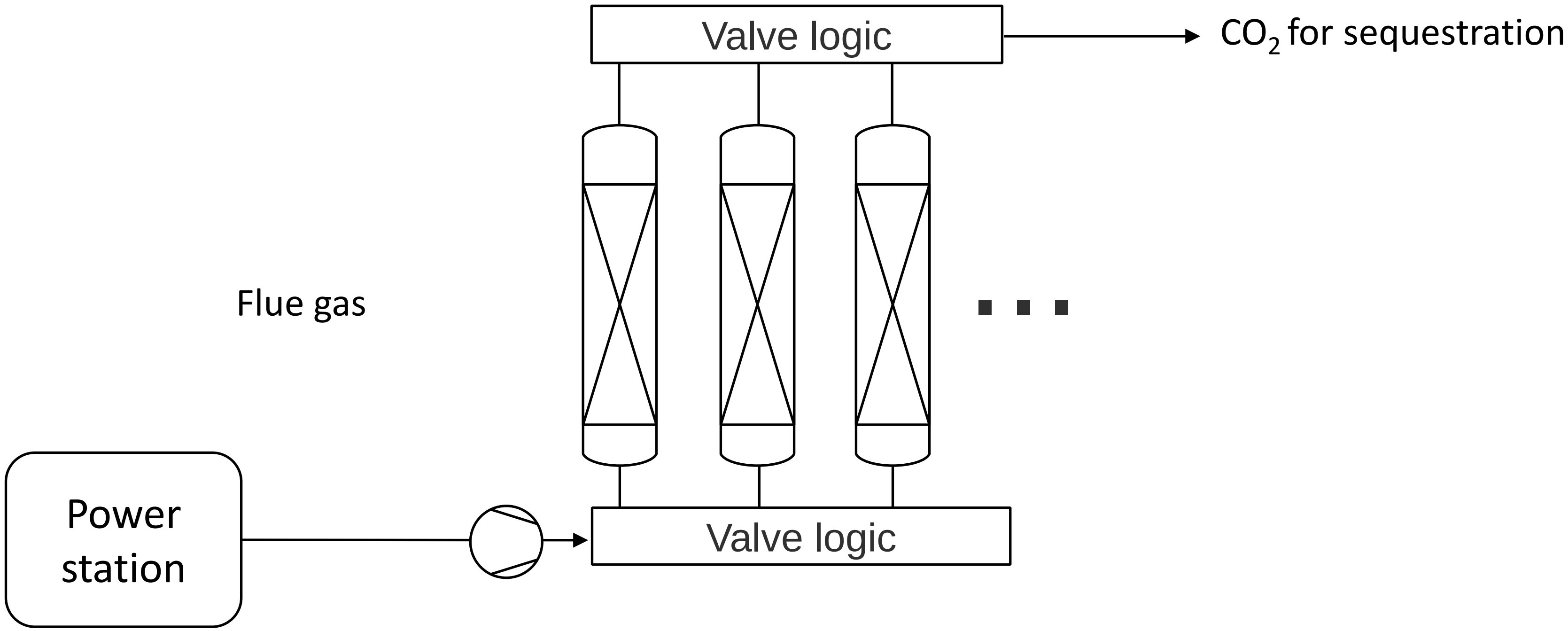
Solid balance: $$(1-\epsilon)\frac{\partial q_i}{\partial t} = -r$$

Momentum balance: $$\frac{\partial P}{\partial z} = -k_f u$$

Energy balance: $$\frac{\partial U}{\partial t} = \ldots$$

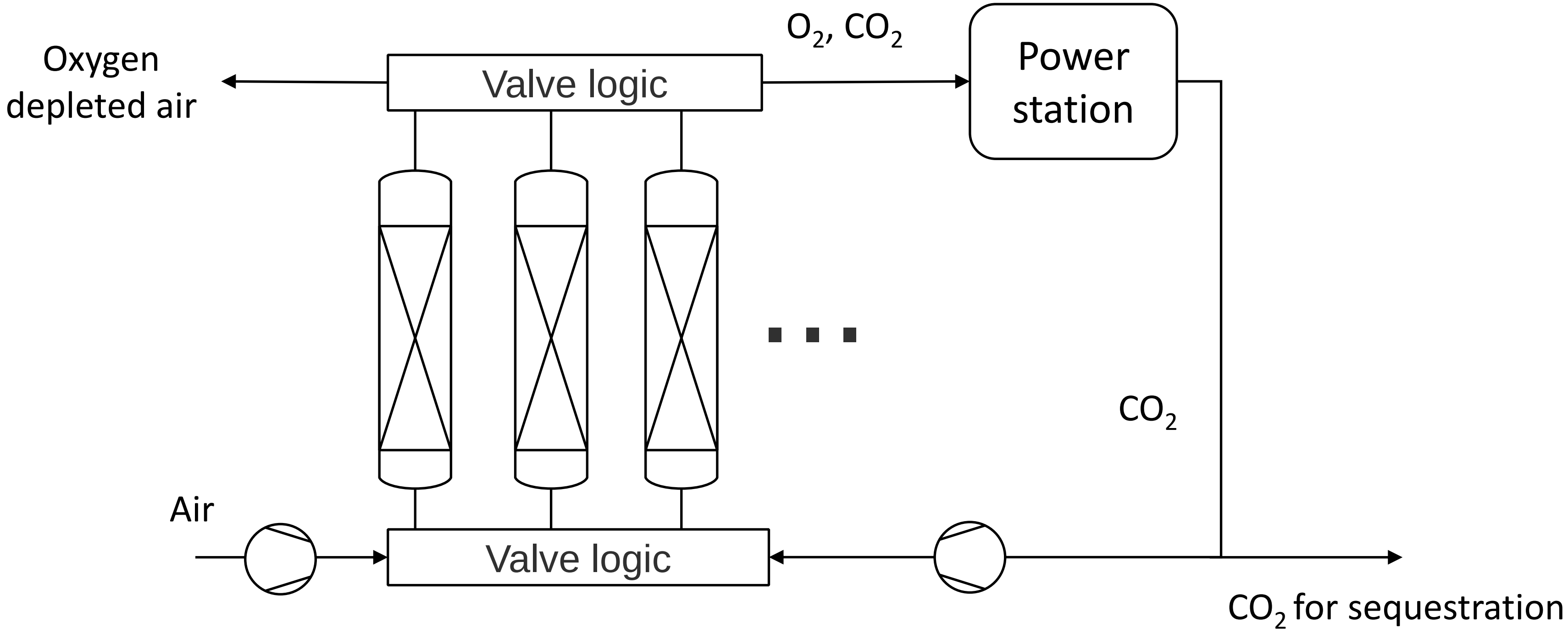
Rate expression: $$r = k(P_i - P^*(q,T))$$

Post combustion capture



- Low temperature sorbents, PSA, power integration.
- High temperature sorbents, heat and power integration or auto thermal.

Air separation



- Low temperature sorbents, PSA, power integration.
- CLAS, high temperature sorbents, heat and power integration or auto thermal.

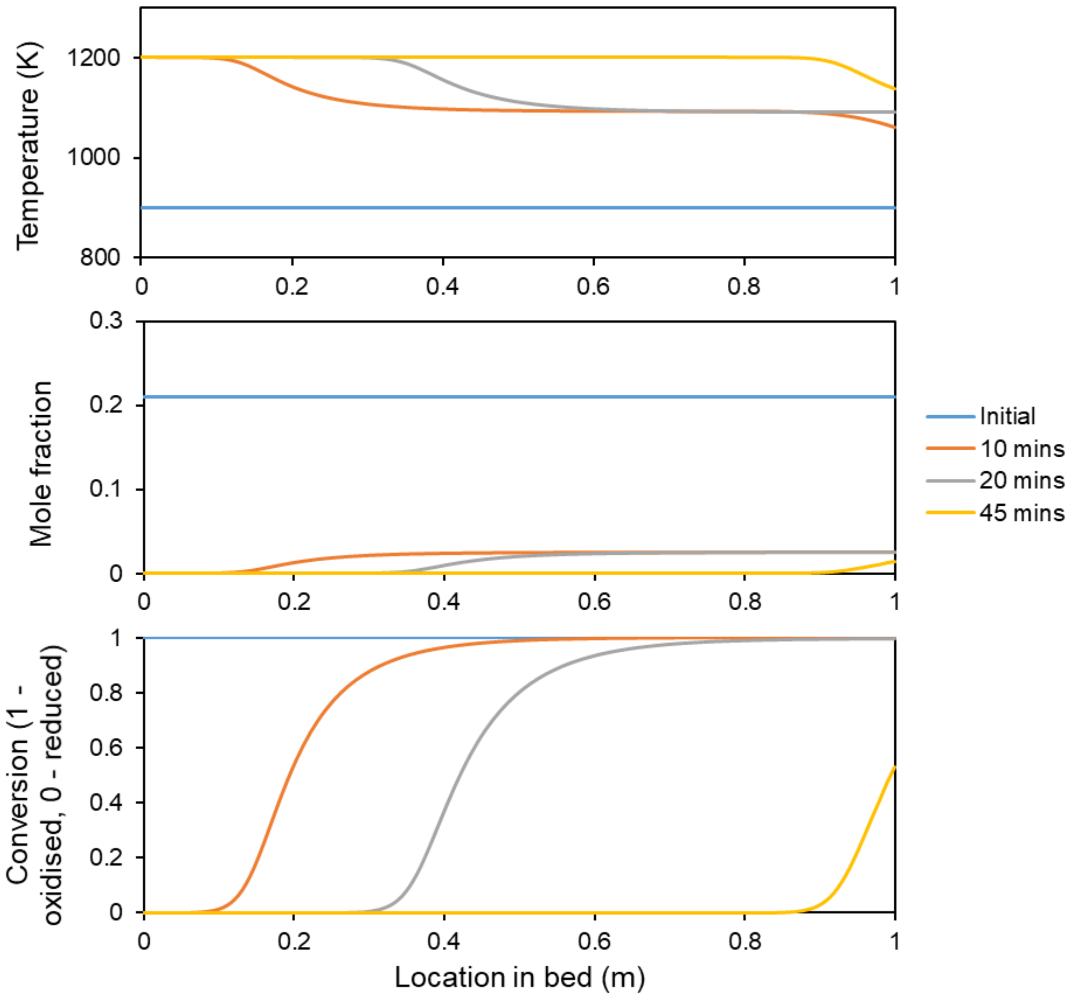
Some sample results….

Initial condition: fully oxidised bed at 900 K and 1 bar, 0.21 O_2 in N_2

At t = 0: Inlet flow 1200 K, 1 bar, pure CO_2

$$CuMn_2O_4 \rightarrow CuMnO_2 + \frac{1}{3}Mn_3O_4 + \frac{1}{3}O_2$$

(Material developed by imperial college)



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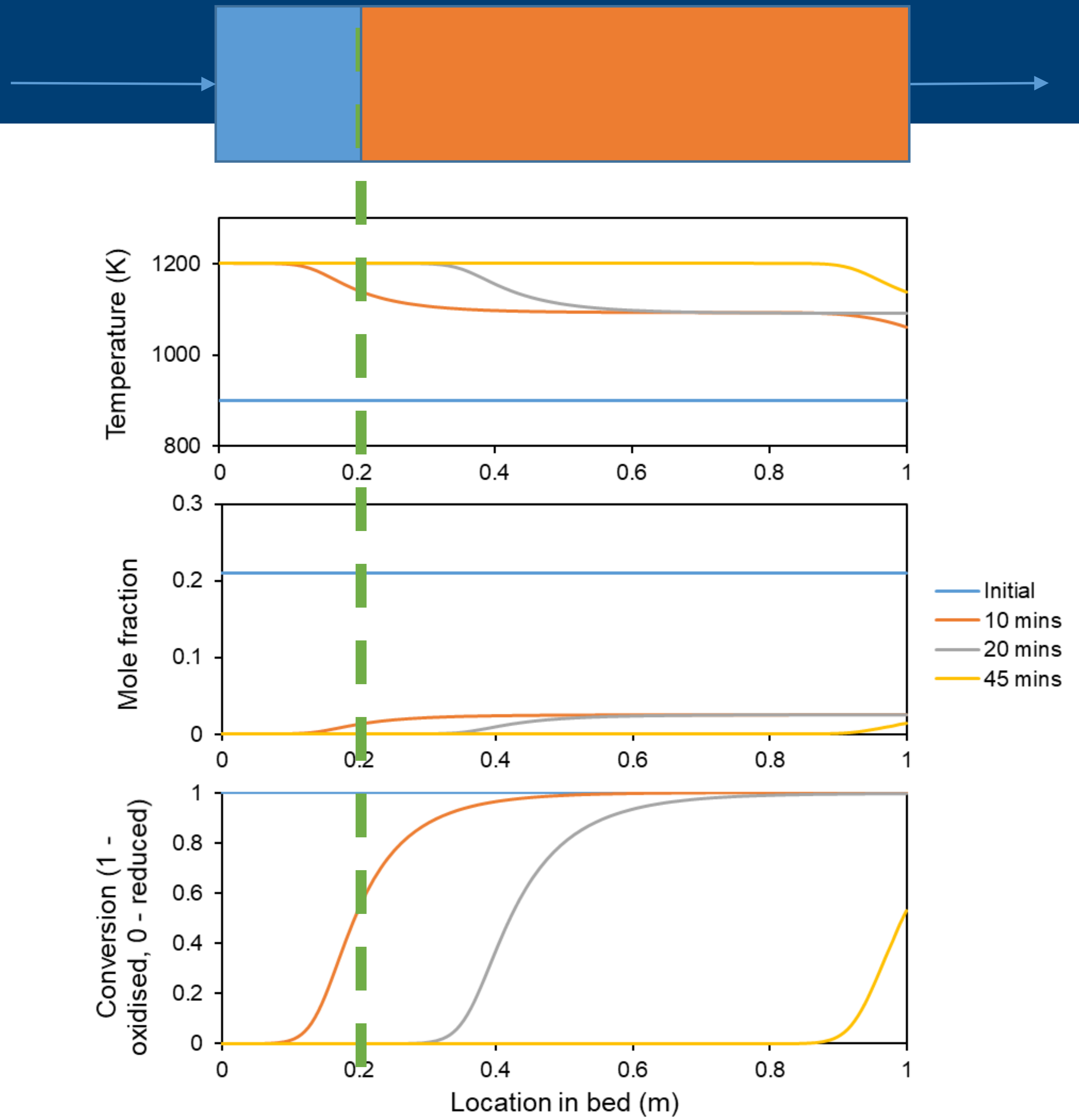

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Follow on work and what we learned…

- Too many variables to allow proper evaluation when using a “detailed model”
- Generalised understanding achieved by combining detailed models and analytical models.

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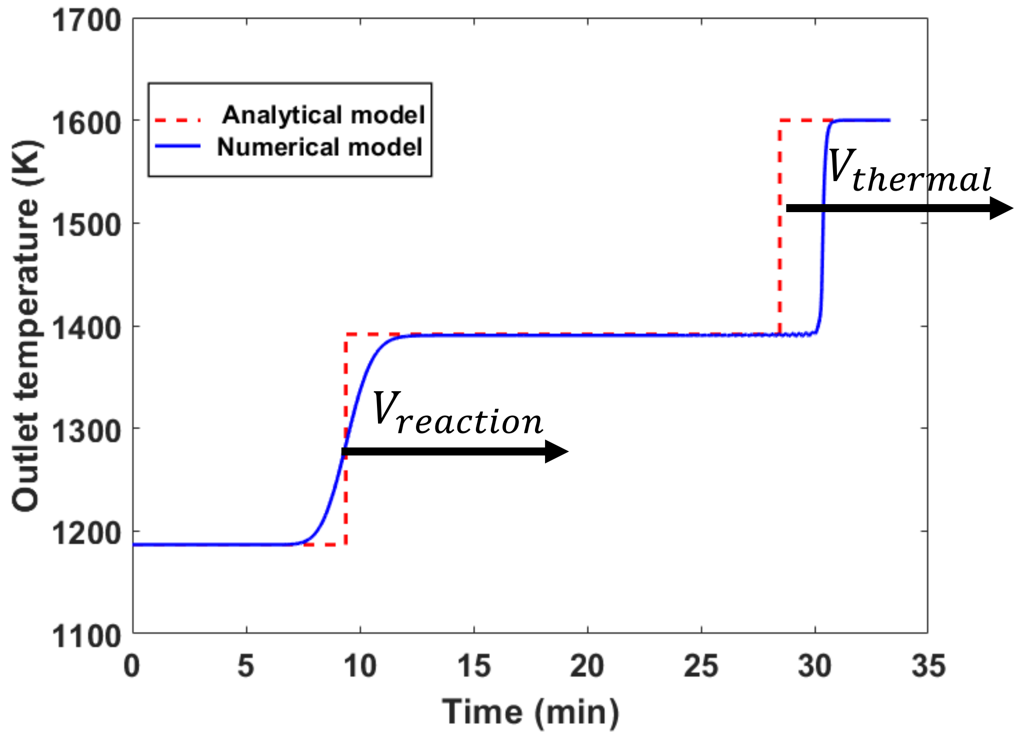

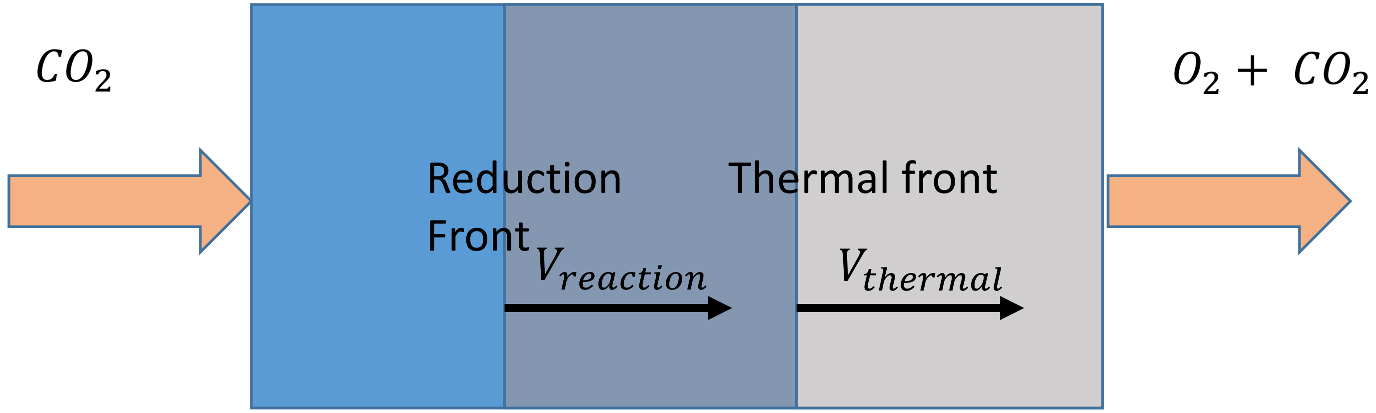

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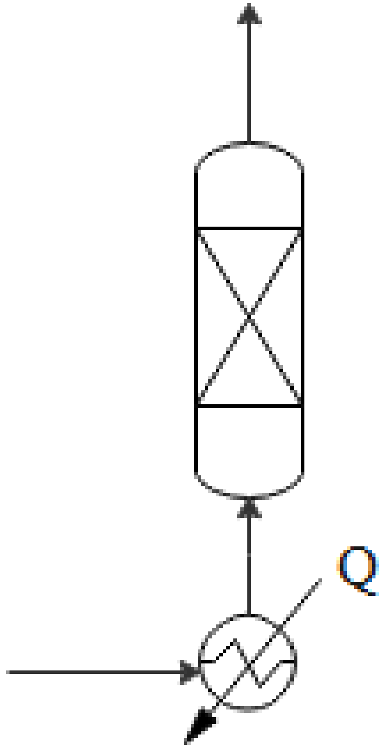
Follow on work and what we learned…

- Materials are largely characterised by the ΔH of reaction
- Materials like the one developed by imperial college are not really suitable for packed beds because of the high ΔH and the lack of back mixing of heat. BUT are ideal for fluidised beds.



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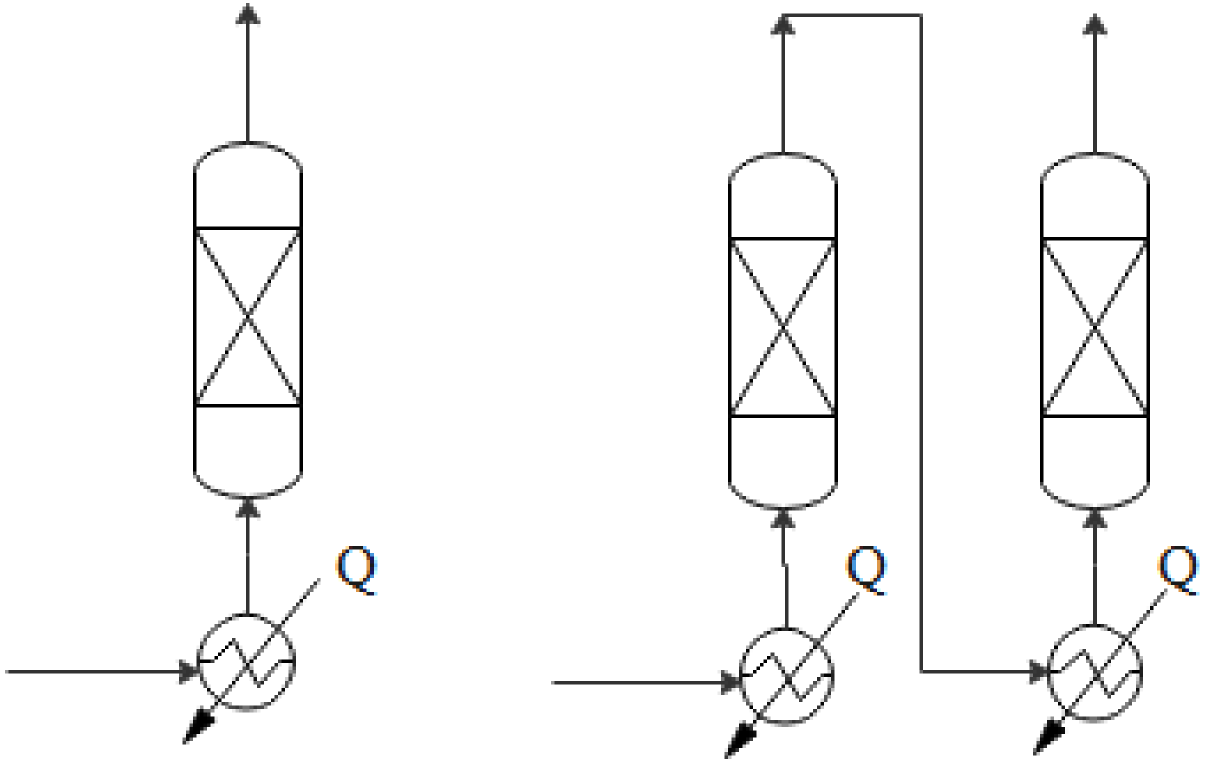

Need multiple beds in series

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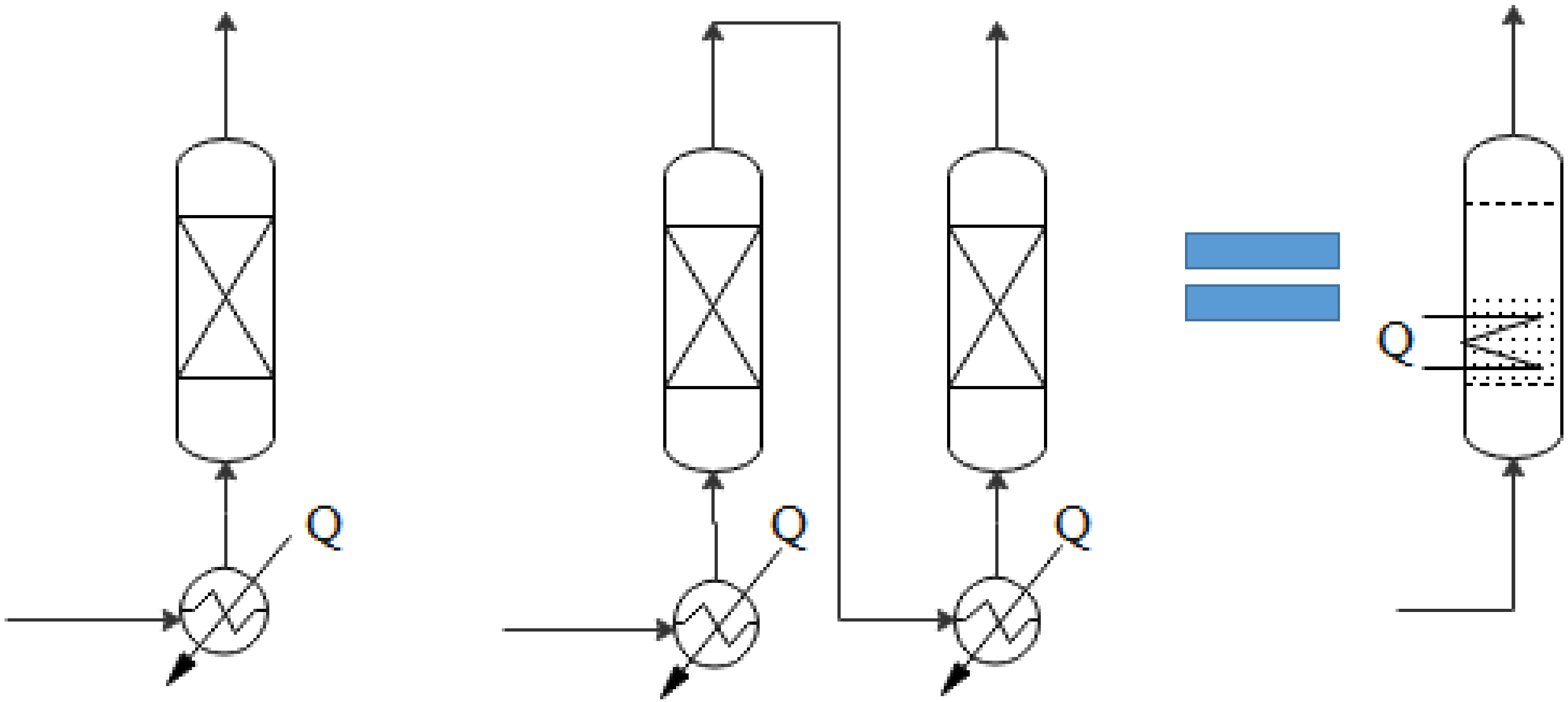

I.e. Fluidised bed

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Follow on work and what we learned…

- Materials are largely characterised by the ΔH of reaction
- High ΔH materials are problematic for purely carbon capture applications, but are ideal for energy storage.

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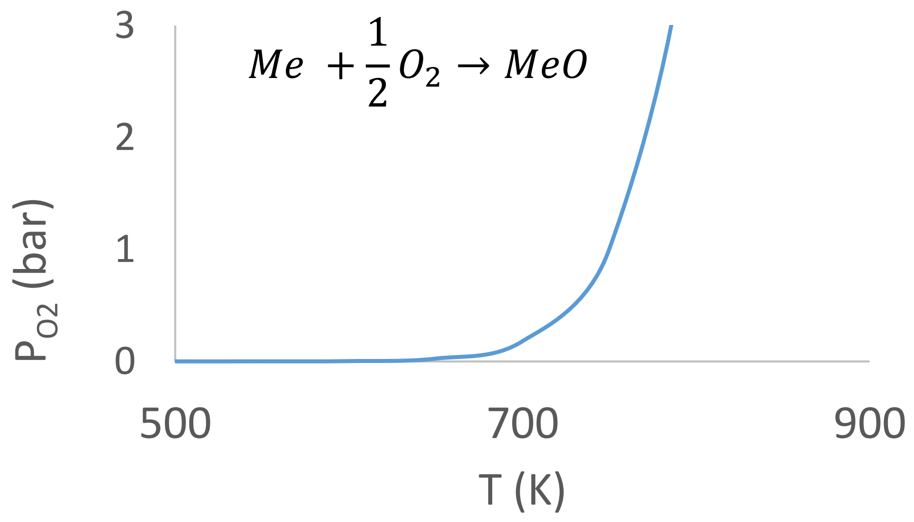
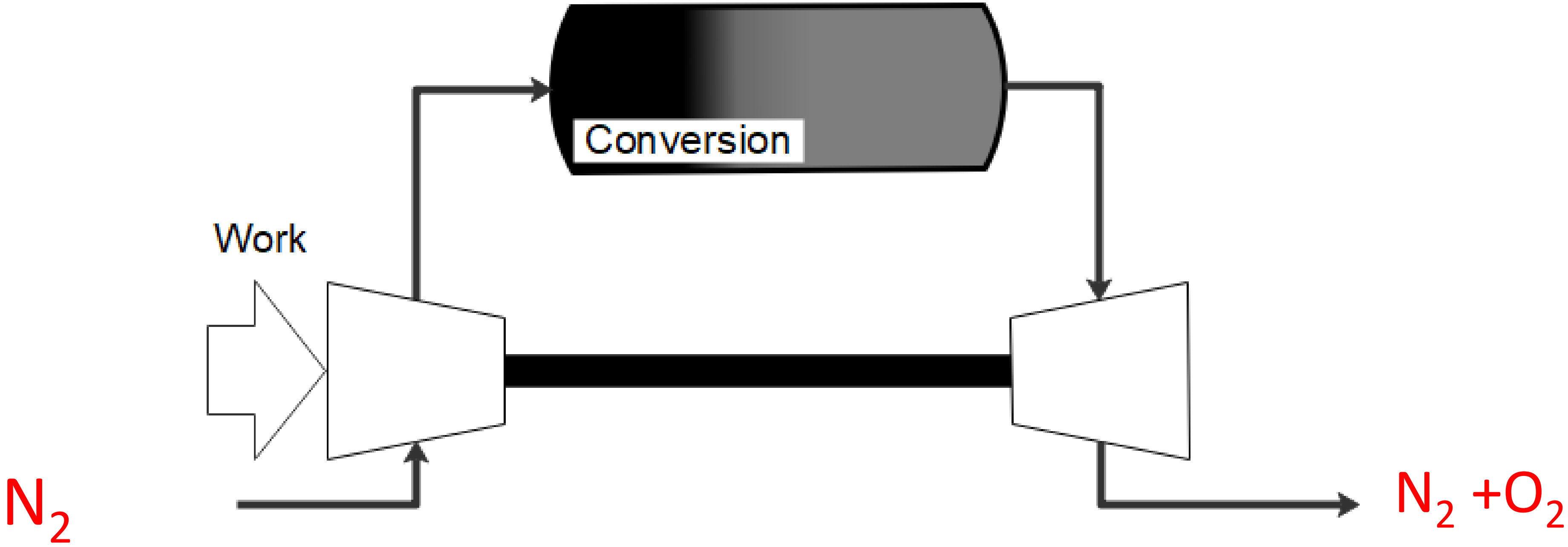


Oxygen transfer material for energy storage

Charging

An inert gas can be used to trigger the decomposition

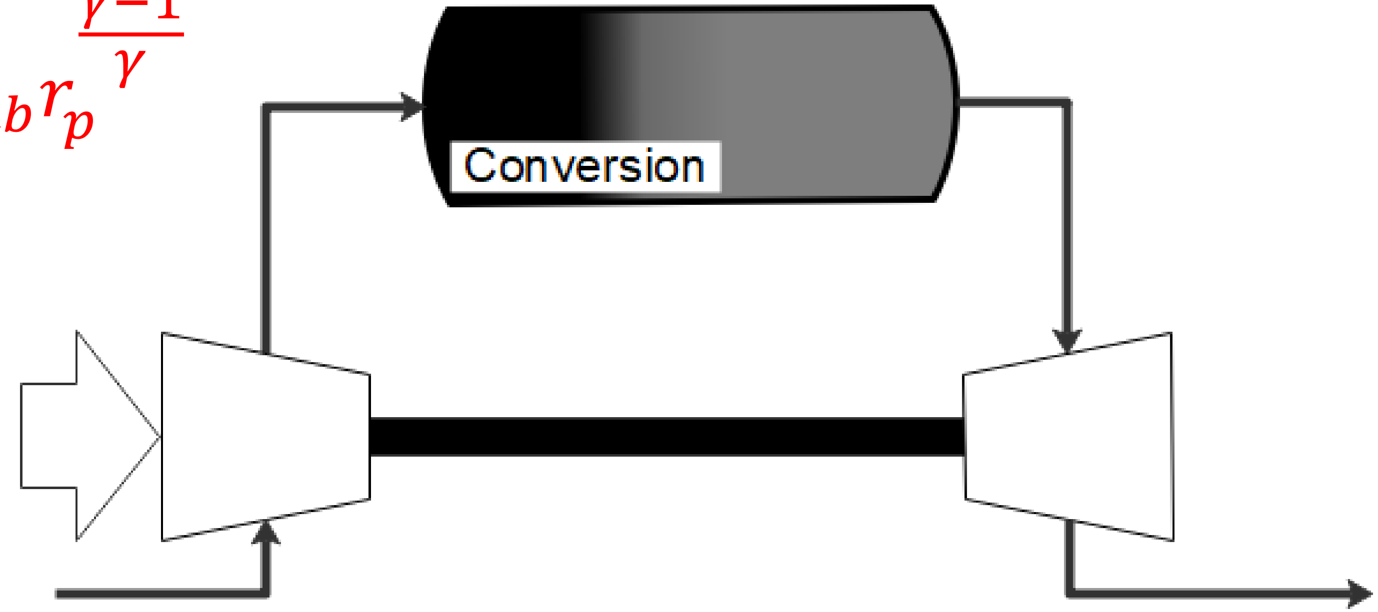


Oxygen transfer material for energy storage

Charging

$$T_c = T_{amb} r_p^{\frac{\gamma-1}{\gamma}}$$

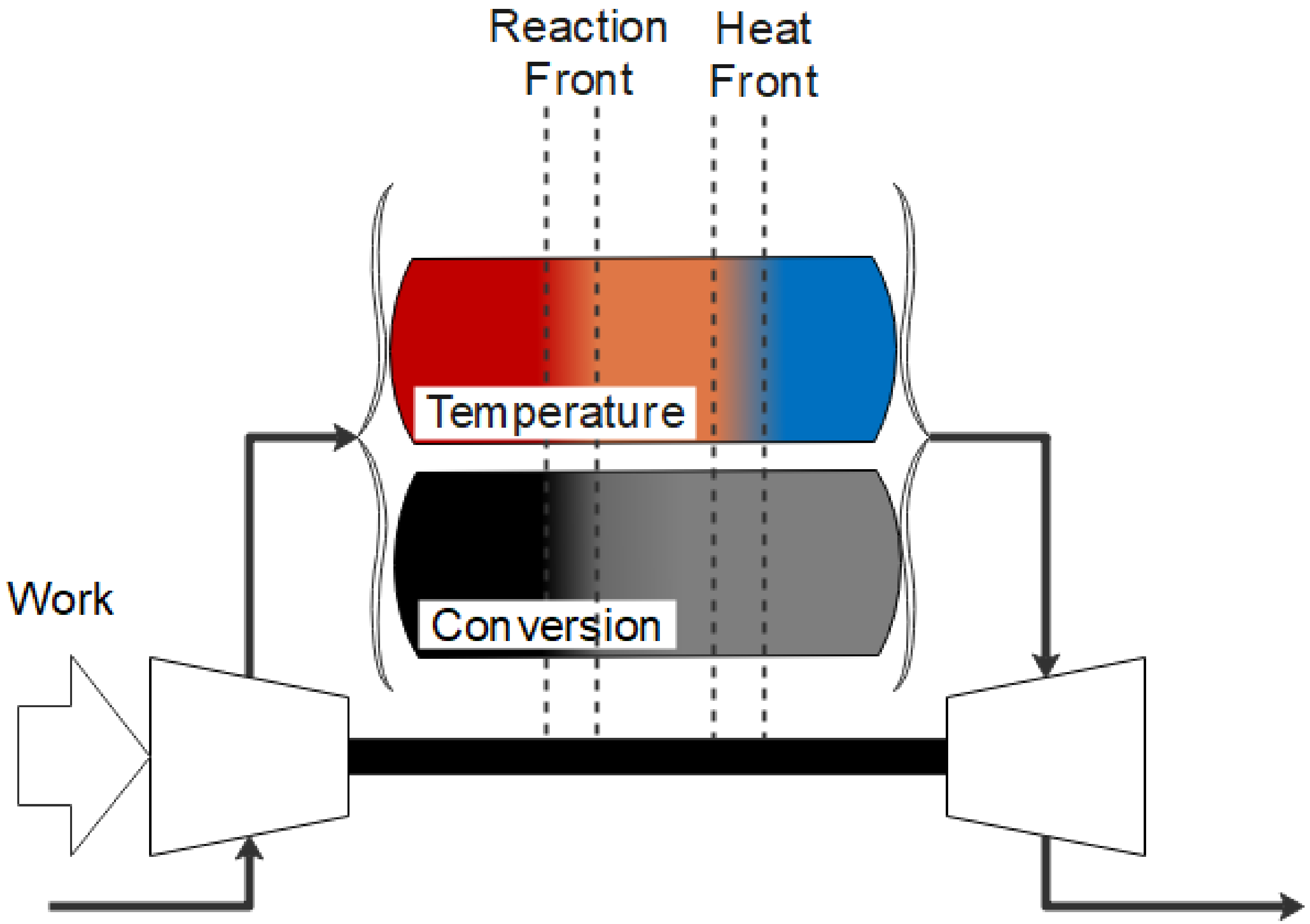
Air



Air + Δ O_2

Oxygen transfer material for energy storage

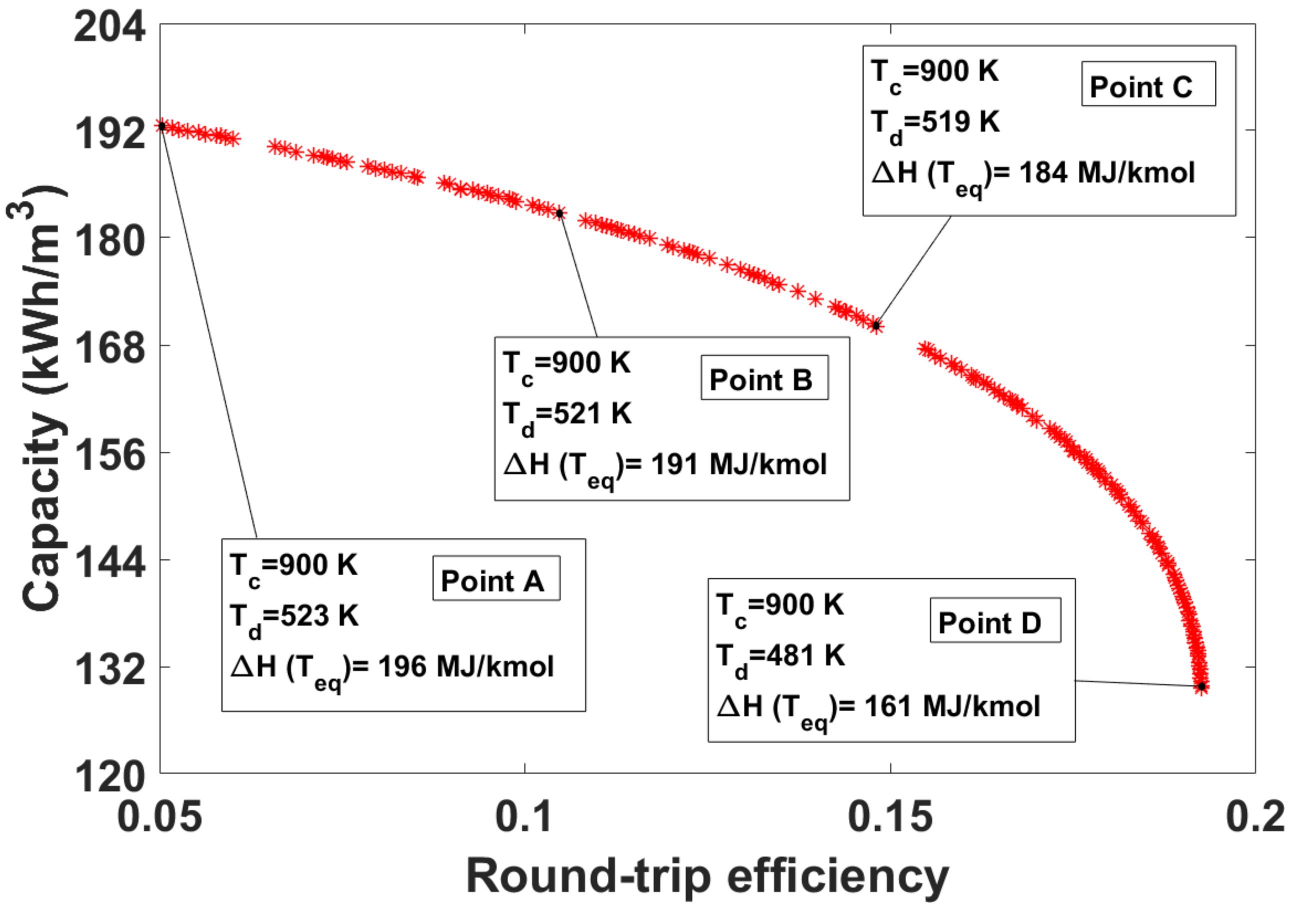
Charging



Air

Air + Δ O_2

Performance of the single bed system

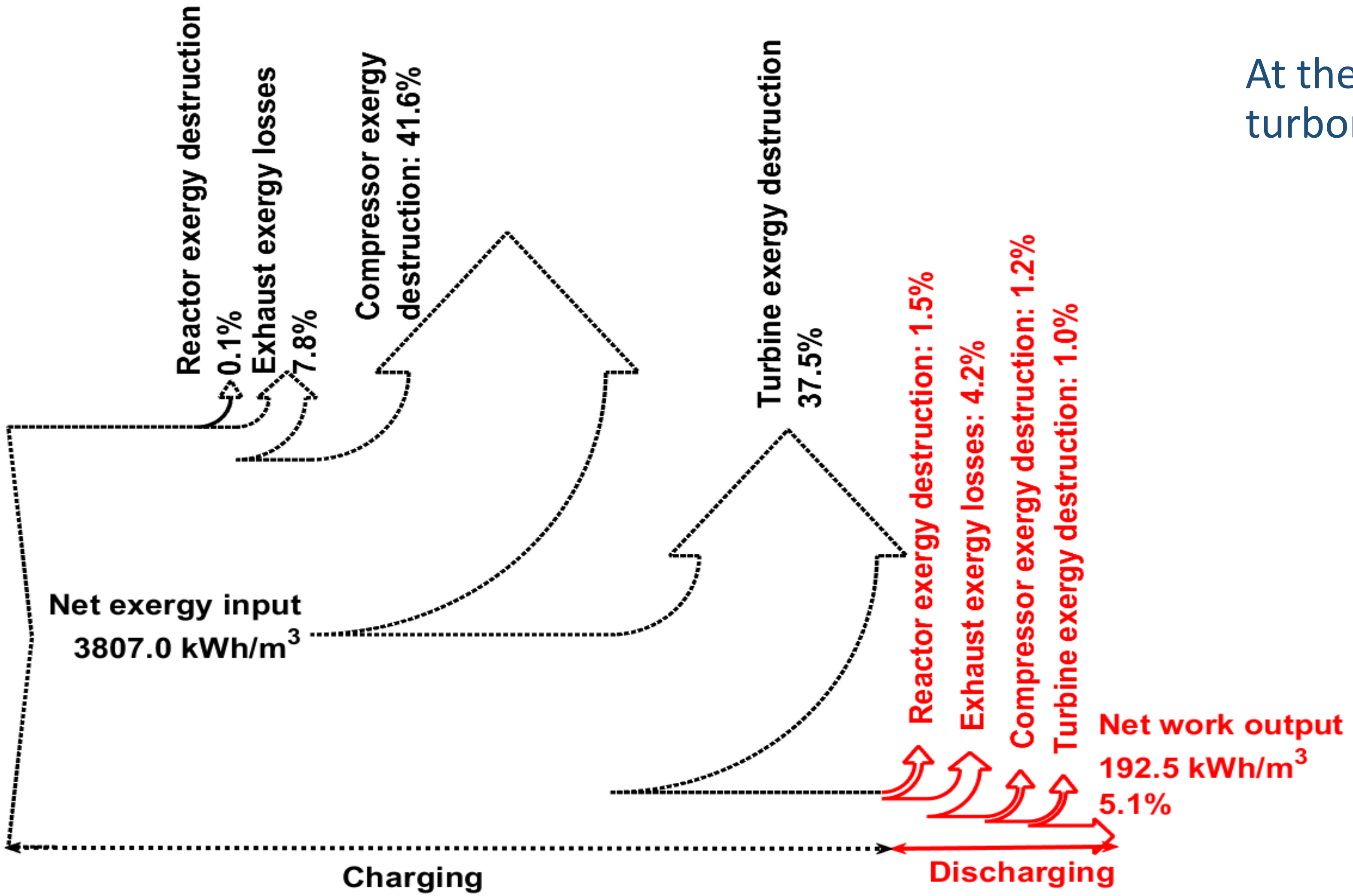


Multi-objective optimization to identify feasible and optimal front (in the Pareto sense).

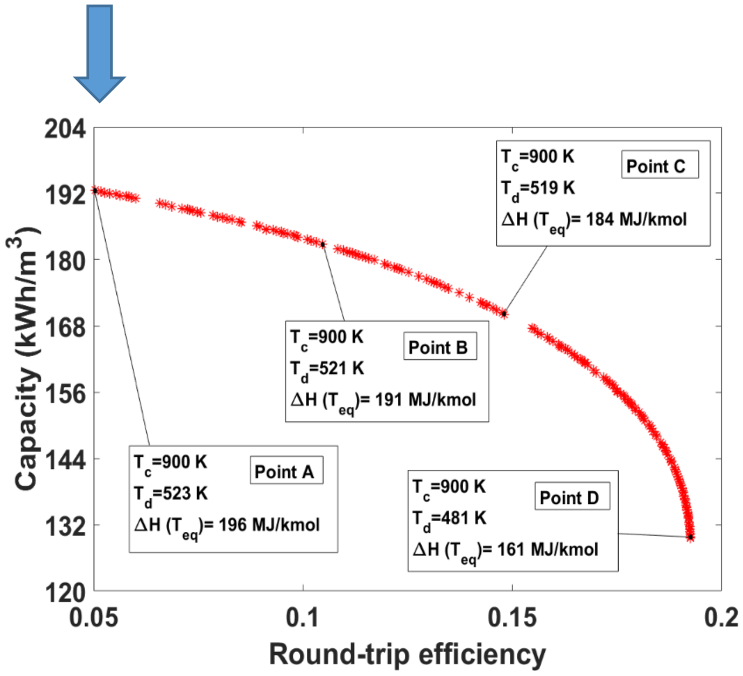
- Trade off between capacity and round trip efficiency
- High round trip efficiency with ideal turbo machinery (not shown here)
- Very low efficiency with non-ideal turbomachinery (shown here)

Saghafifar, M., Schnellmann, M.A., Scott, S.A., 2020. Chemical looping electricity storage. Applied Energy 279, 115553. https://doi.org/10.1016/j.apenergy.2020.115553

Performance of the single bed system (Exergy Map)



At the high capacity end, large losses in turbomachinery



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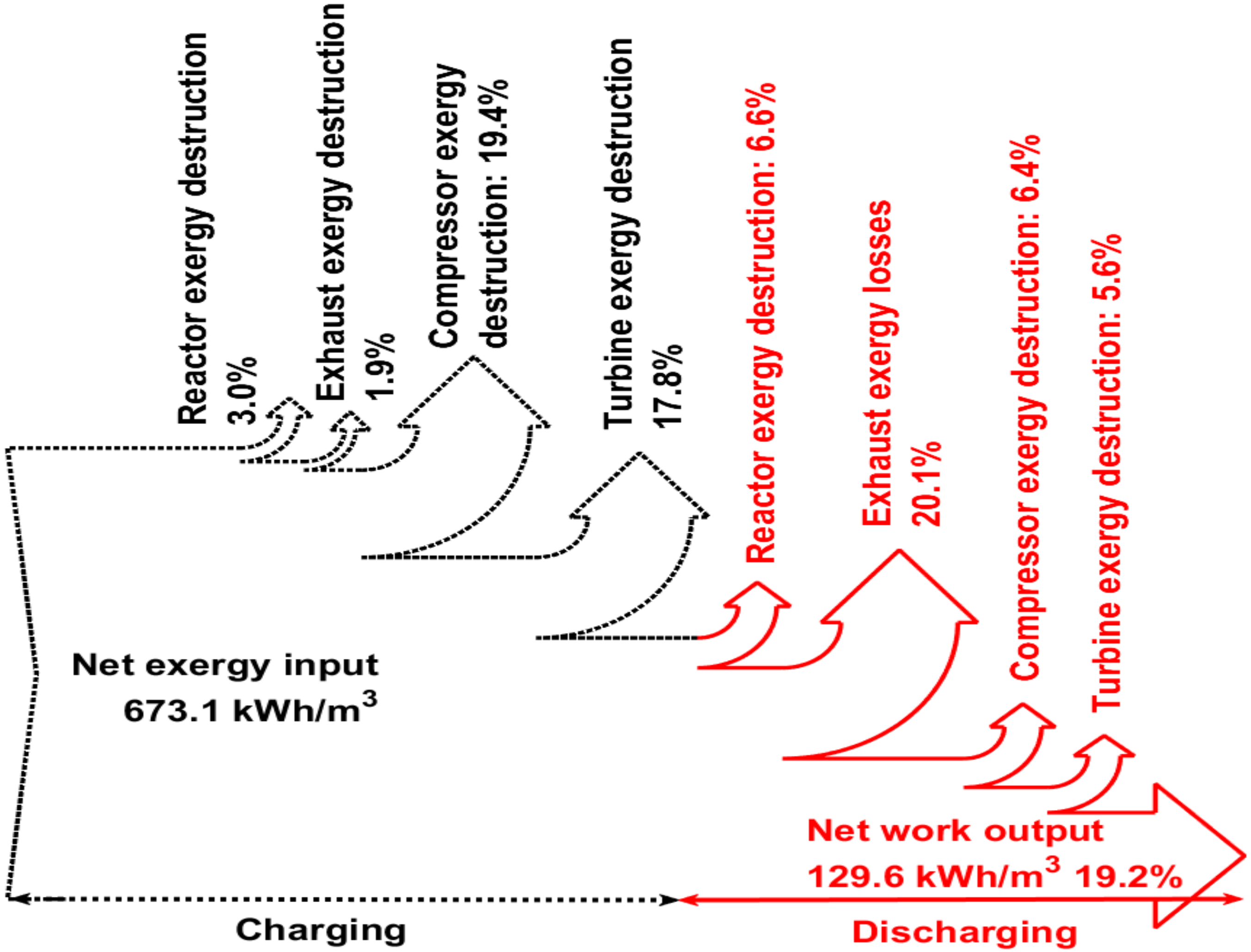
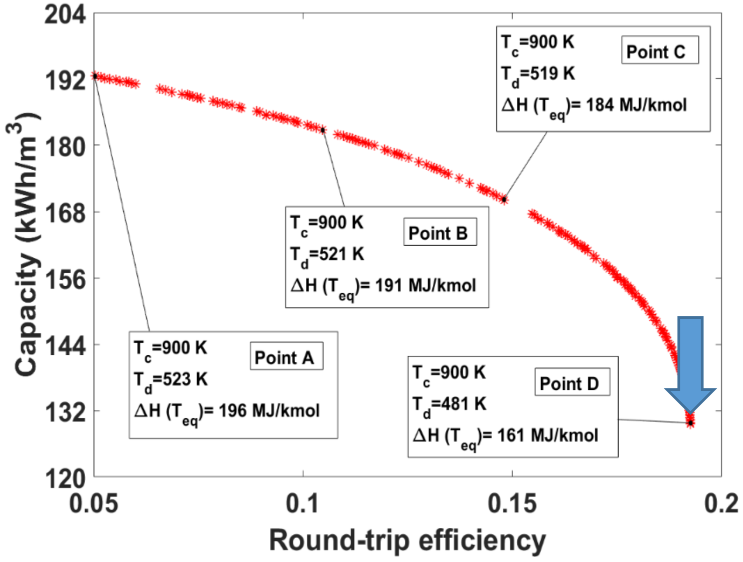


At the “high” efficiency end, large exhaust losses.



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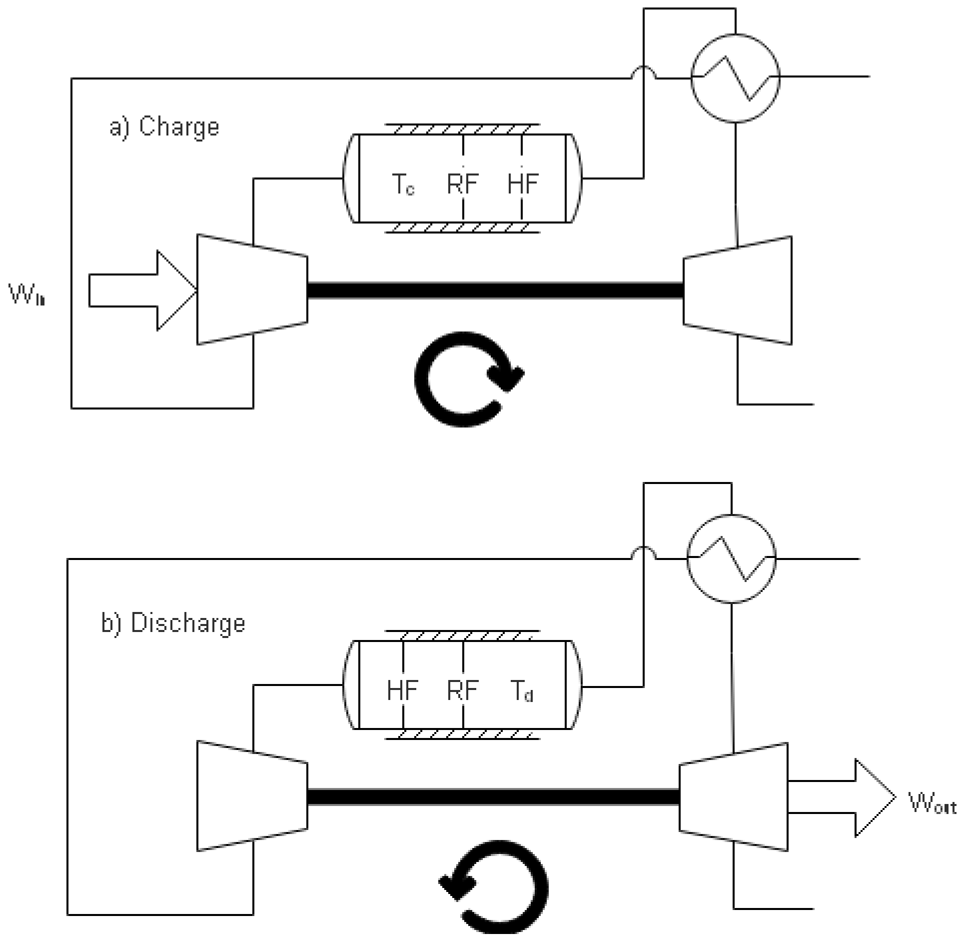
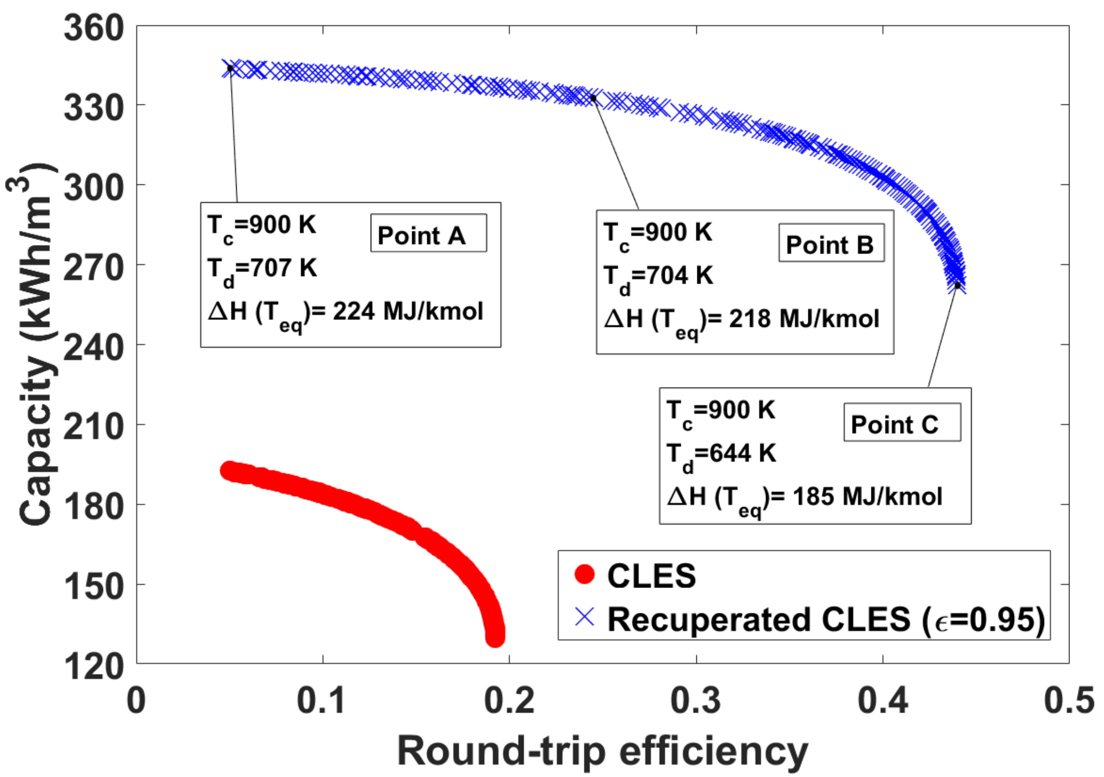
Improved performance – recuperated cycle





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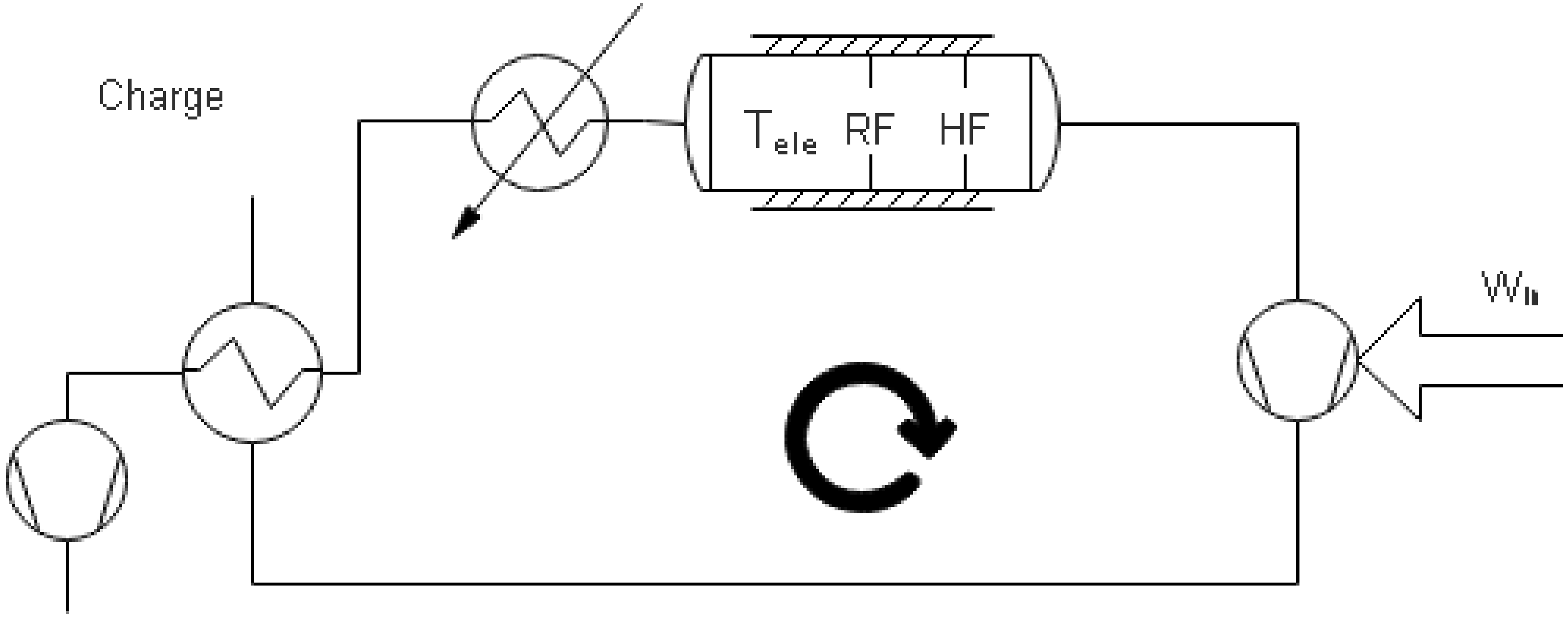
Opening up the material space

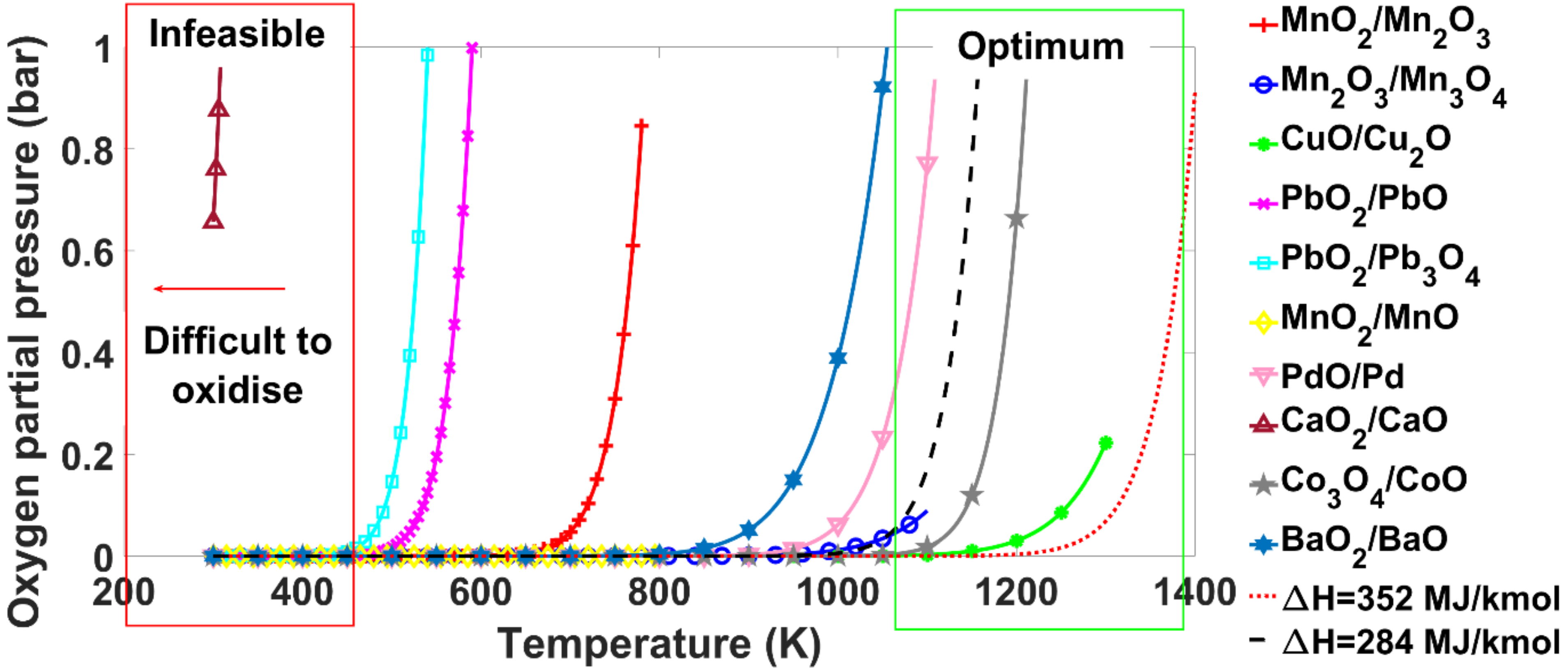
Want to use material with large ΔH, but these have high equilibrium temperatures



- Using a simple electrical heater decouples the temperature at the reaction front from the pressure
- The recuperator reduces exhaust loses and losses in converting electricity to heat

Saghafifar, M., Scott, S.A., 2021, Chemical looping electricity storage for high temperature materials, Chemical Engineering Journal, submitted

Materials



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