FLUIDIZED BEDS FOR CONCENTRATED SOLAR POWER WITH THERMAL/THERMOCHEMICAL ENERGY STORAGE

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SolarPACES International Particle Technology Working Group (PTWG) Workshop
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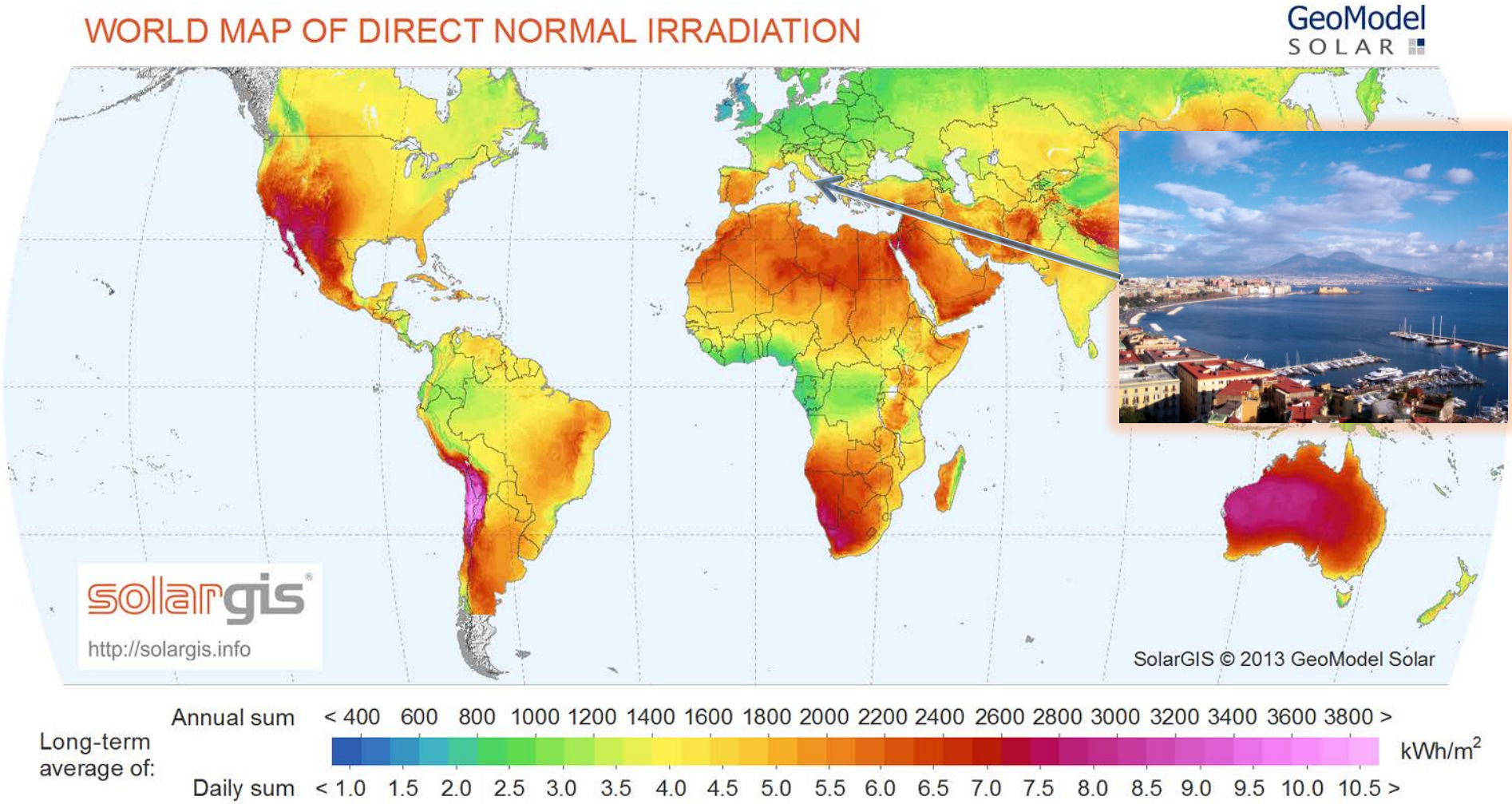
RESEARCH GROUP LOCATION



ACKNOWLEDGMENTS

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- Responsible project leader of the Consortium:
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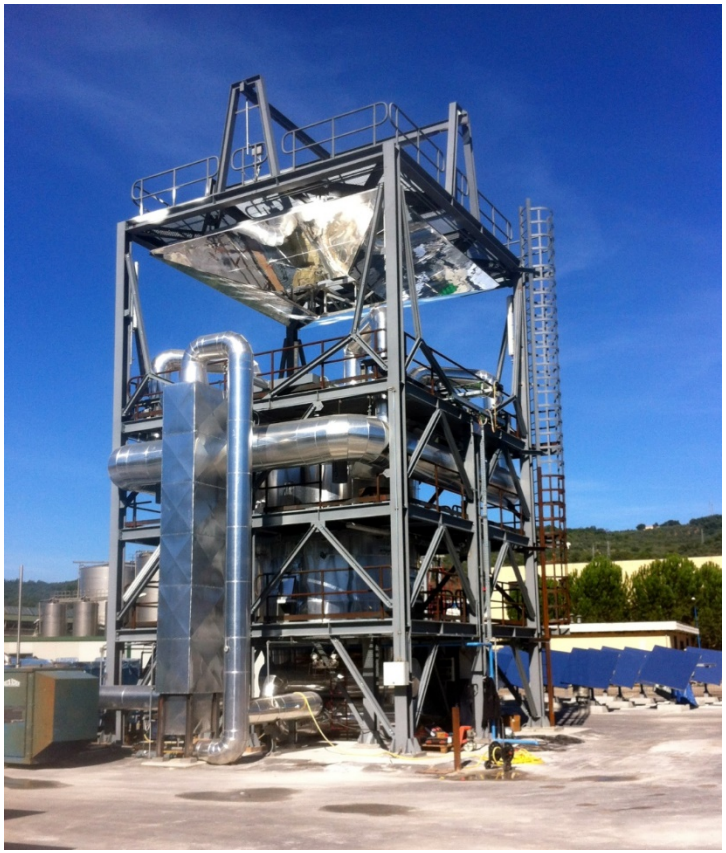
- Several students for their activity during Master thesis

THE AIM OF SOLTESS PROJECT

Development of a novel concept (STEM) of Concentrated Solar Power (CSP) cogeneration system with inherent thermal energy storage. The system is based on a compartmented dense gas fluidized bed and aims at the following targets:

- Reduction of the Levelized Energy Cost (LEC)
- Simple - Robust - Reliable
- Modular concept
- Near-zero environmental impact
- Easy hybridization

STEM PLANTS



the 125kWth peak load CSP plant at Buccino

the 2MWth peak load CSP plant at San Filippo del Mela

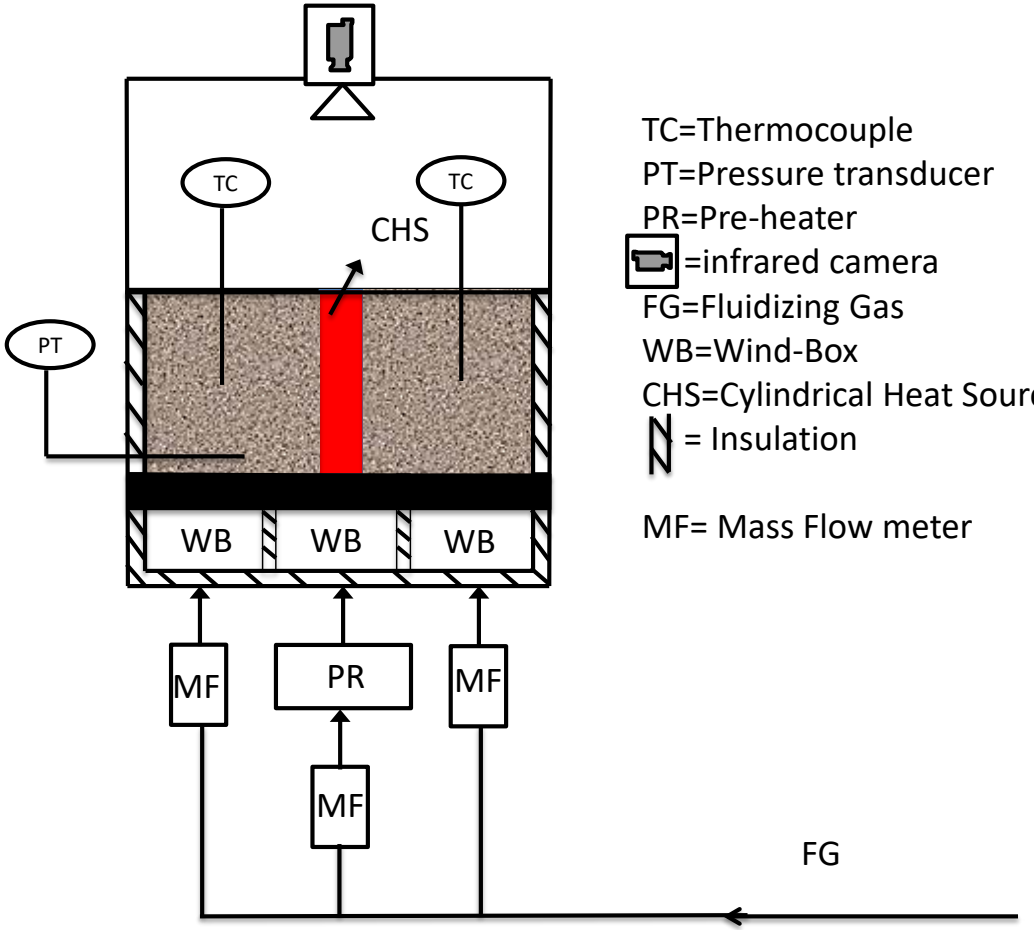
WHY A FLUIDIZED BED SOLAR RECEIVER?

Thermal characteristics:

- large bed-to-surface heat transfer coefficients, in the order of several hundreds of W/m^2K, which can be tuned by acting on the fluidization parameters
- large effective thermal diffusivities, in the order of 0.001 m^2/s, associated with convective transfer due to bubble-induced and/or gulfstream motion of fluidized solids

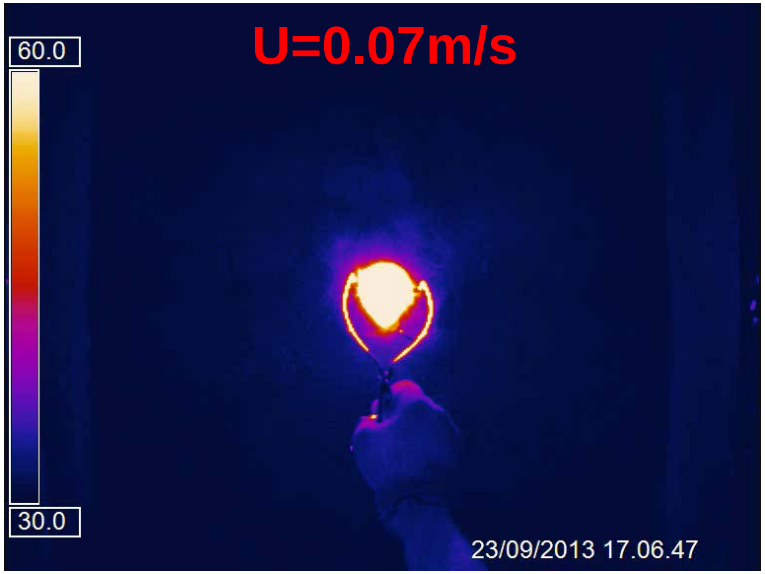
		steel	concrete	molten salts	graphite	fluid beds
ρ	kg/m^3	7800	2200	2000	1600	**~1000**
k	W/mK	40	1.5	1	50	**~2000**
c_p	kJ/kgK	0.6	0.85	1.5	1.5	**~1**
α	m^2/s	8.5E-06	8.0E-07	3.3E-07	2.1E-05	**~2E-03**

HEAT TRANSFER MECHANISMS



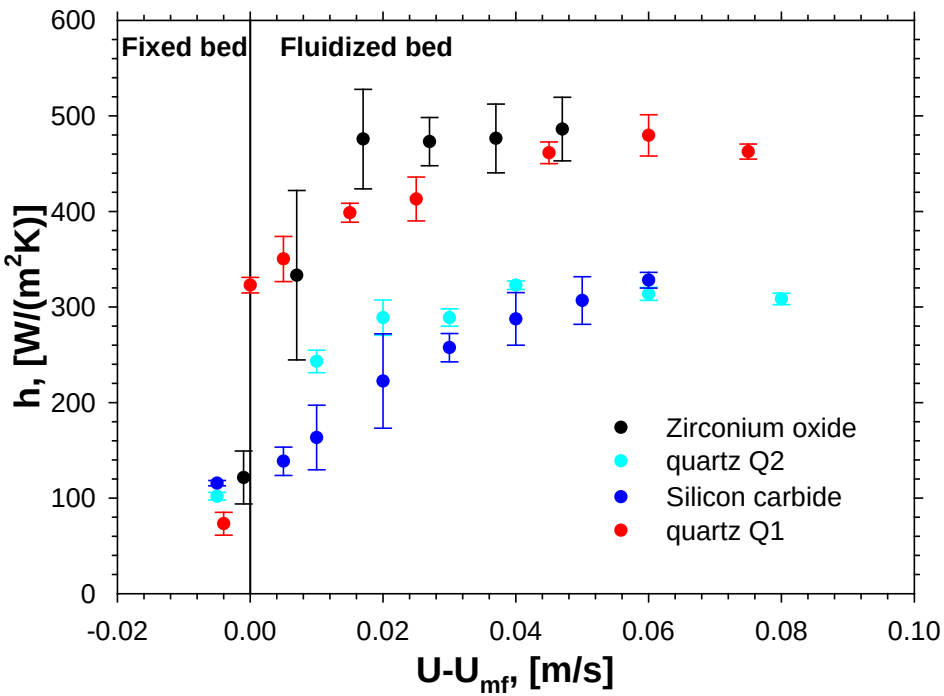
TC=Thermocouple
PT=Pressure transducer
PR=Pre-heater
=infrared camera
FG=Fluidizing Gas
WB=Wind-Box
CHS=Cylindrical Heat Source
= Insulation

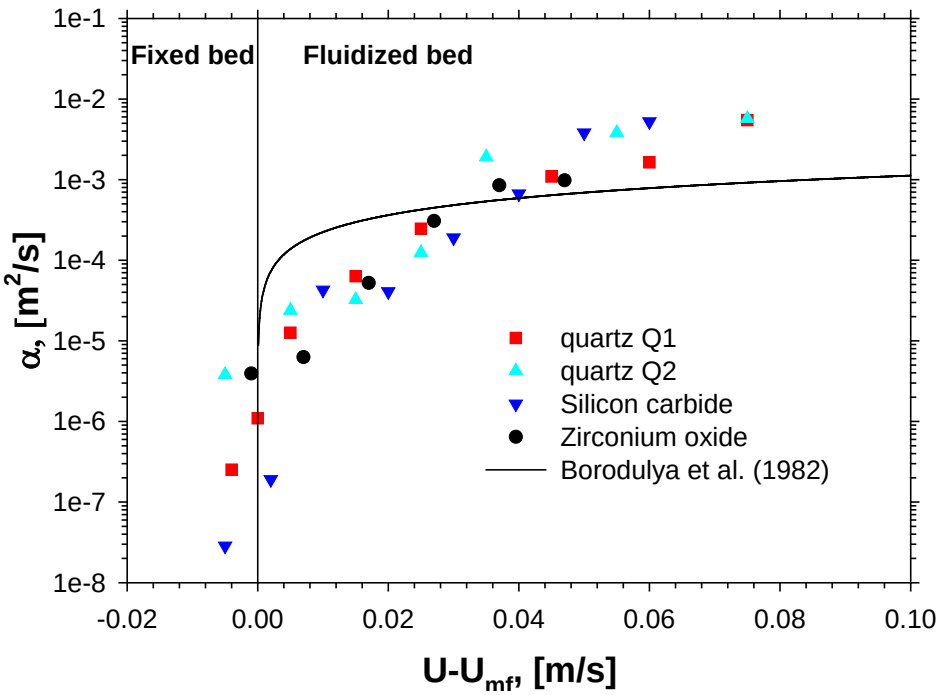
MF= Mass Flow meter



Solimene et al., CFB-11 Proceedings of the 11th International Conference on Fluidized Bed Technology (2014)

HEAT TRANSFER MECHANISMS



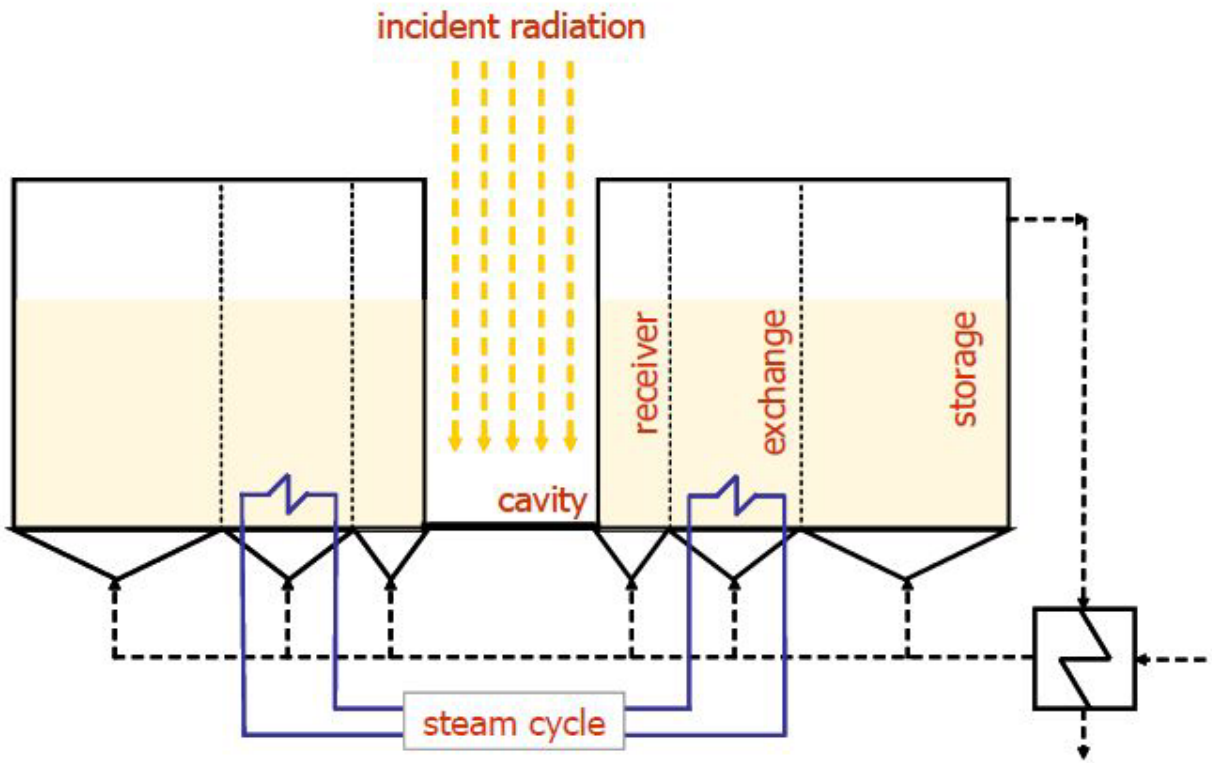


Solimene et al., CFB-11 Proceedings of the 11th International Conference on Fluidized Bed Technology (2014)

COMPARTMENTED DENSE GAS FLUIDIZED BEDS

System optimized to accomplish three complementary tasks:

- RECEIVER: Collection of highly concentrated (100-1000 suns) incident solar radiation
- EXCHANGE: heat transfer to the working fluid of the thermodynamic cycle
- STORAGE: thermal energy for equalizing the inherent time-variability of the incident solar radiation



The system is also equipped with an external heat exchanger for partial recovery of the enthalpy of the effluent gas

Solimene et al., SolarPACES (2016)

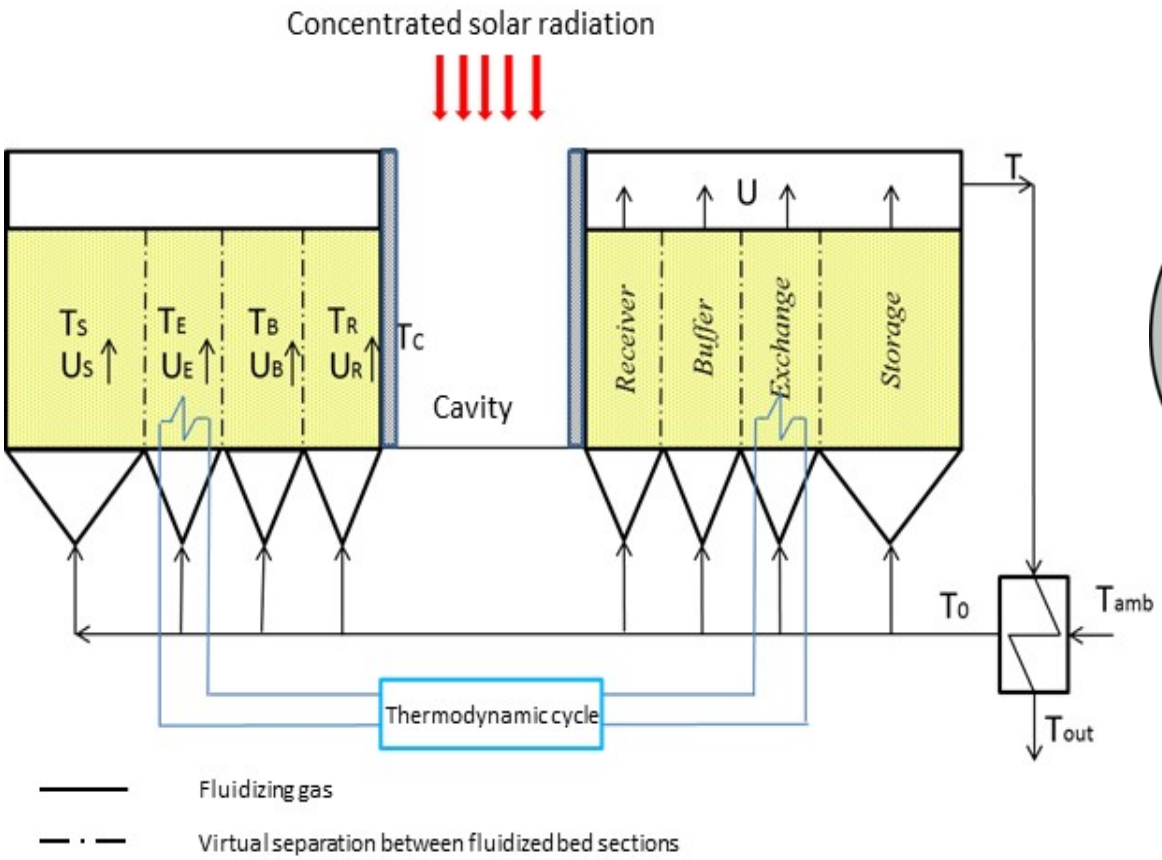
COMPARTMENTED DENSE GAS FLUIDIZED BEDS

- The bed is compartmented by proper design of the windbox. No physical separation is introduced within the bed to preserve the fluidized bed thermal properties

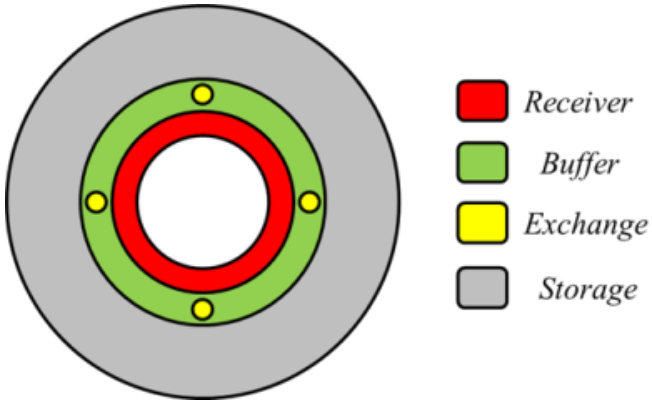
- Each zone/compartment is fluidized independently of the others, with the aim of establishing optimal fluidization conditions in each zone, consistently with its function.

- Assumption: the compartmented windbox ensures effective independent control of the desired fluidization regime in each zone, even in the absence of physical separations between the zones inside the bed.

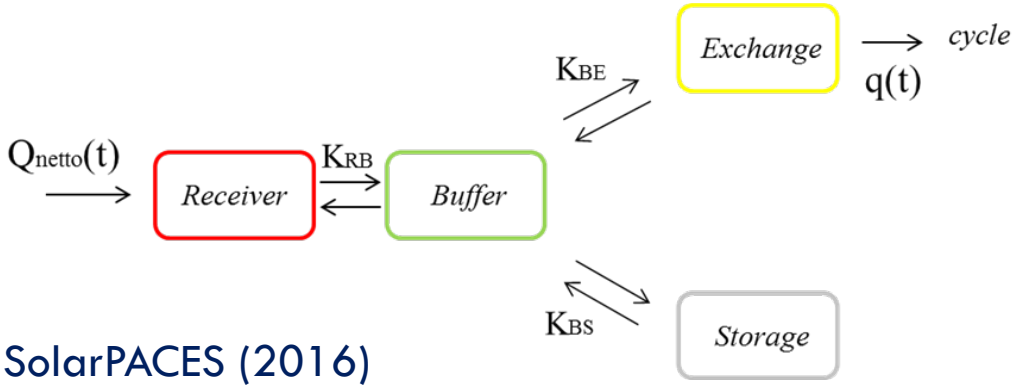
Dynamic modeling of the Compartmented fluidized bed receiver



TOP VIEW OF THE FLUIDIZED BED COMPARTMENTS



SCHEMATIC OF THE ENERGY FLUXES



Buffer compartment is devoted to distribute energy fluxes between the other compartments

Solimene et al., SolarPACES (2016)

Study cases

- Case A: Reference case (even and steady fluidization). Fluidized bed operated without partitioning of the fluidizing gas and permanently fluidized at constant and uniform gas superficial velocity (0.033 m/s).

- Case B: Non-controlled compartmented case (uneven and steady fluidization). R, E, B and S sections fluidized independently of each other. U=0.02 m/s in the S and B sections. U= 0.1 m/s in R and E sections (to provide locally optimal values of h_{bed}). The overall gas flow rate in Case B is the same as that in Case A.

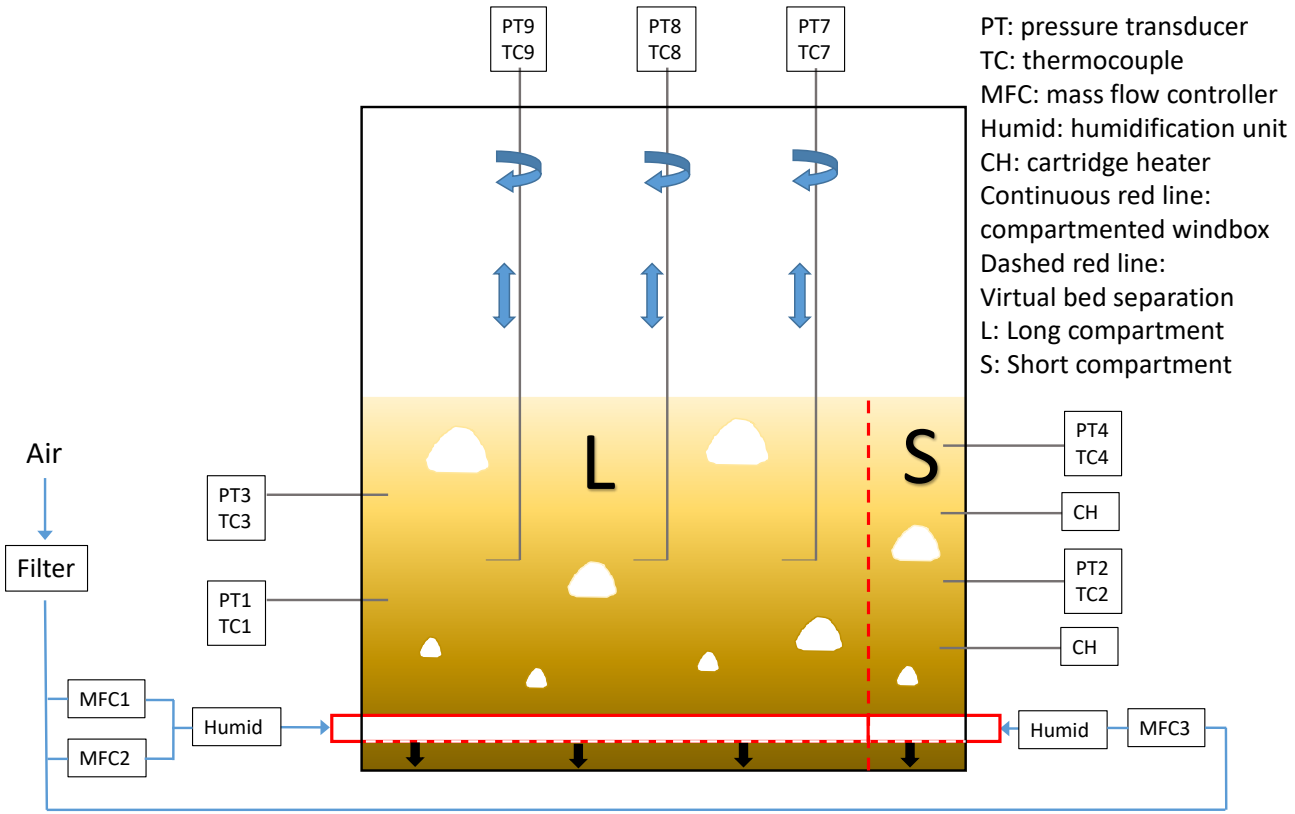
- Case C: Controlled compartmented case (uneven and unsteady (pulsed) fluidization). Case B with additional implementation of a control strategy aimed at minimizing energy losses and keeping constant the firm capacity load.

Comparison of the day-averaged outputs of the model

Case	Power, kW						Efficiency, -		
	Incident radiation	Reflected radiation	Fluidizing gas losses	Cavity radiative losses	Cavity natural convection losses	**Power to steam cycle**	cavity	fluidized bed	**Overall**
A	707	7.5	99	150	79	**370**	0.66	0.79	**0.52**
B	707	7.5	81	89	70	**462**	0.78	0.85	**0.65**
C	707	7.5	36	78	47	**540**	0.81	0.94	**0.76**

Solimene et al., SolarPACES (2016)

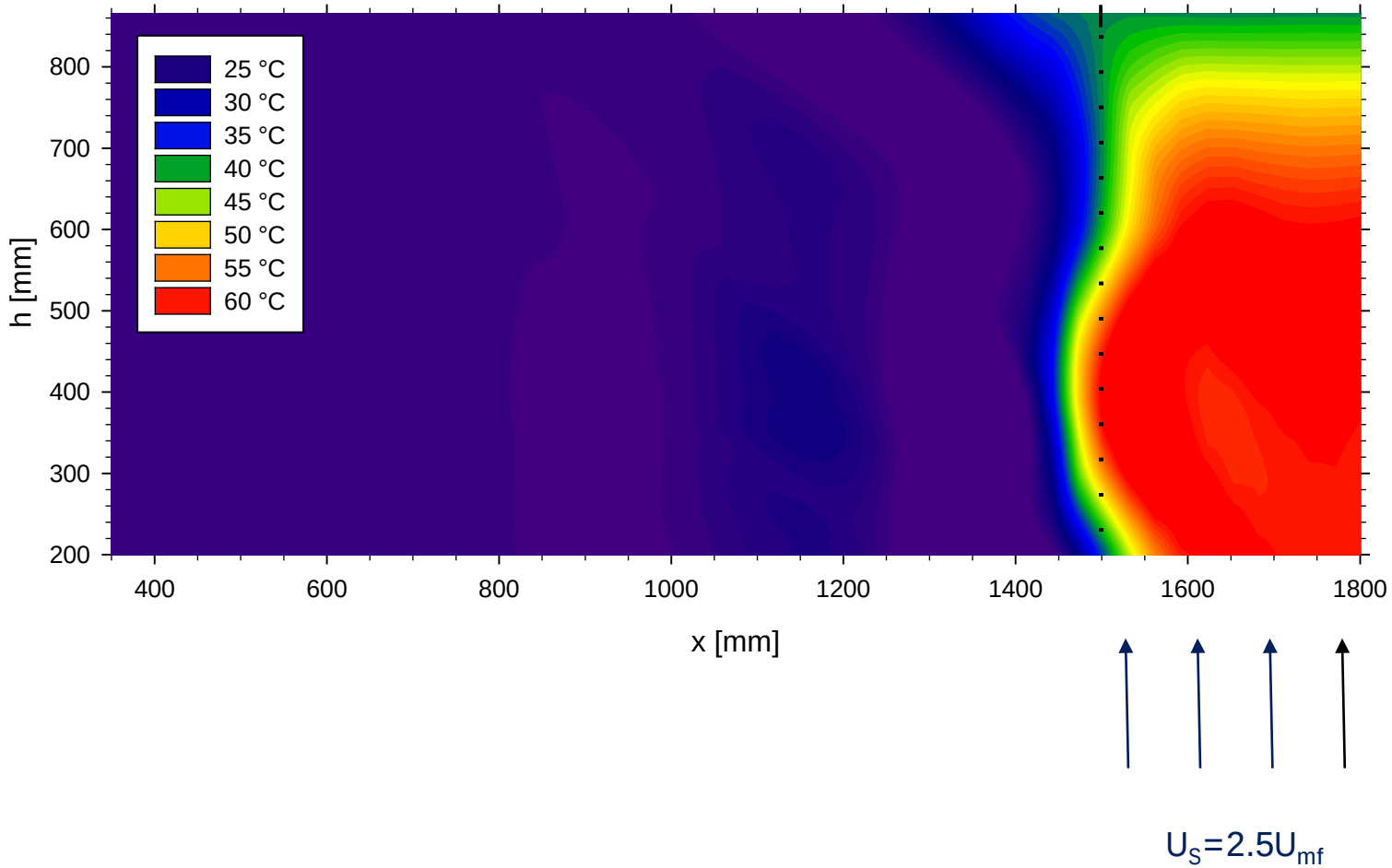
COMPARTMENTATION AND THERMAL DIFFUSIVITY



Migliozzi et al., Powder Technolgy in press (2016)

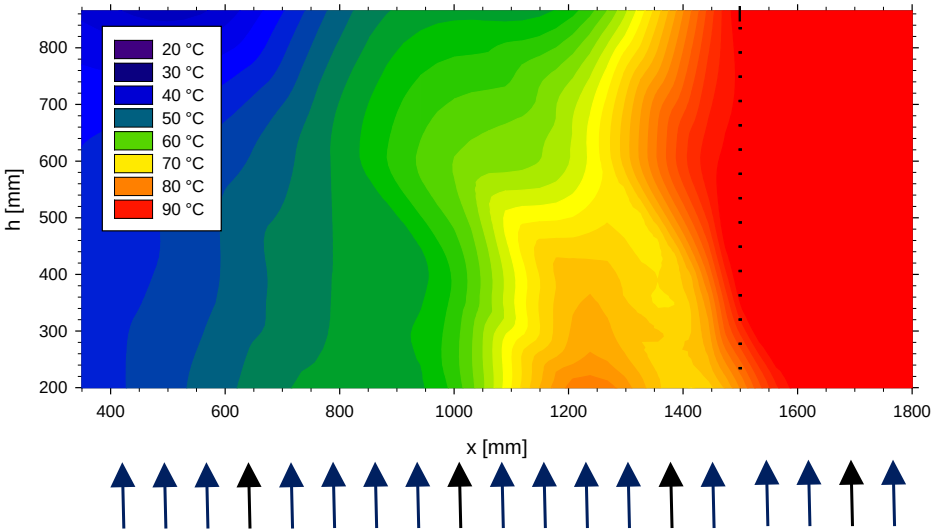
- ✓ near-2D fluidized bed (2850x1860x200mm) with a thickness large enough to prevent extensive wall effects for bubbles smaller than 120 mm.
- ✓ two spargers acting as gas distributors intentionally of different length so to establish uneven bed fluidization with asymmetric patterns.
- ✓ the corresponding sections of the fluidized bed, as L (*long*), and S (*short*)

COMPARTMENTATION

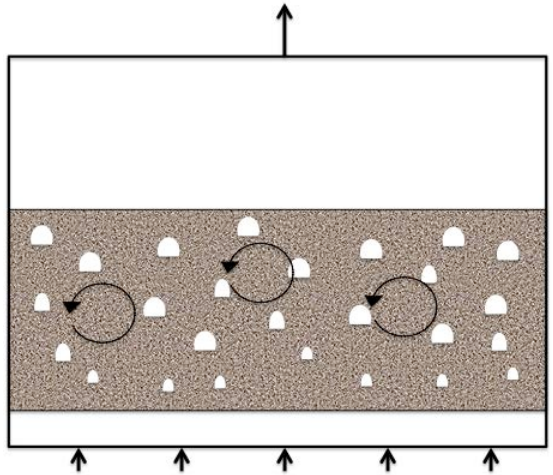


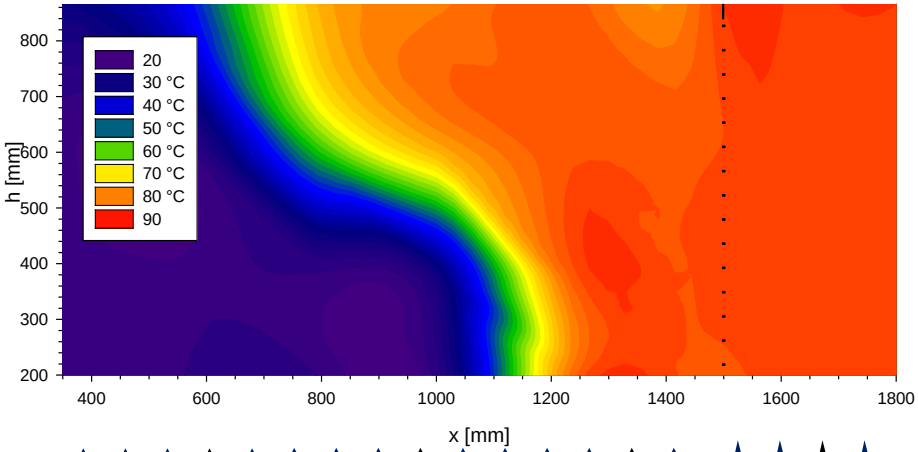
$U_S=2.5U_{mf}$

THERMAL DIFFUSIVITY: EVEN vs UNEVEN



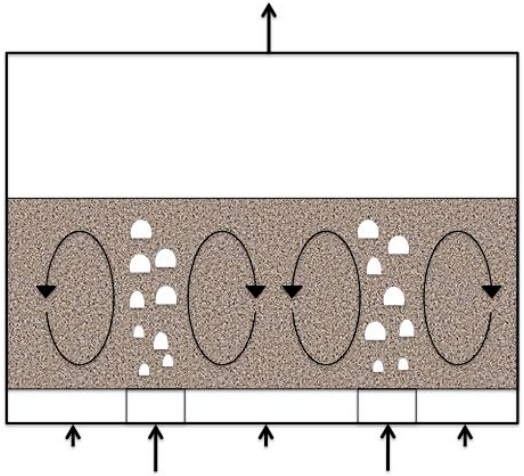
$U_L = U_S = 2.5U_{mf}$





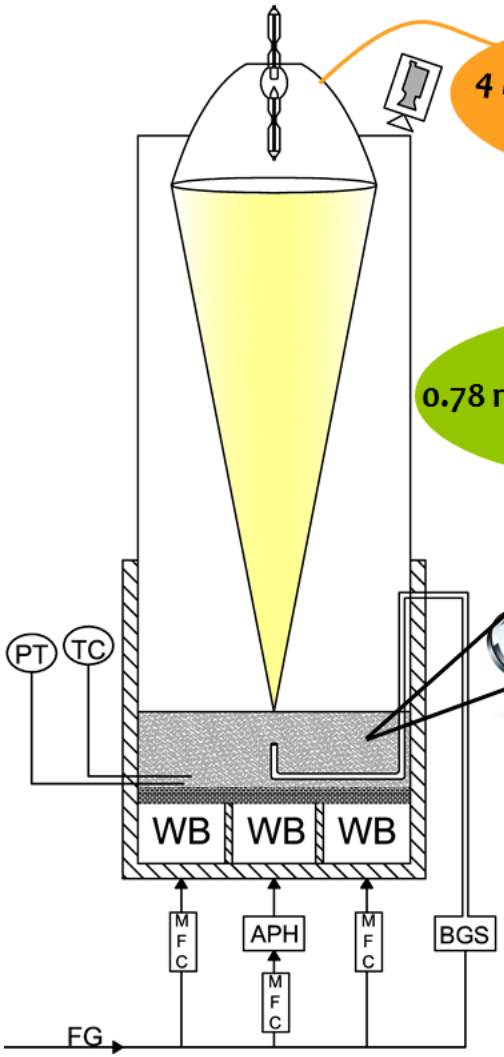
$U_L = U_{mf}$

$U_L = 8.5U_{mf}$



Salatino al., Powder Technology (2016)

DIRECTLY IRRADIATED FLUIDIZED BED



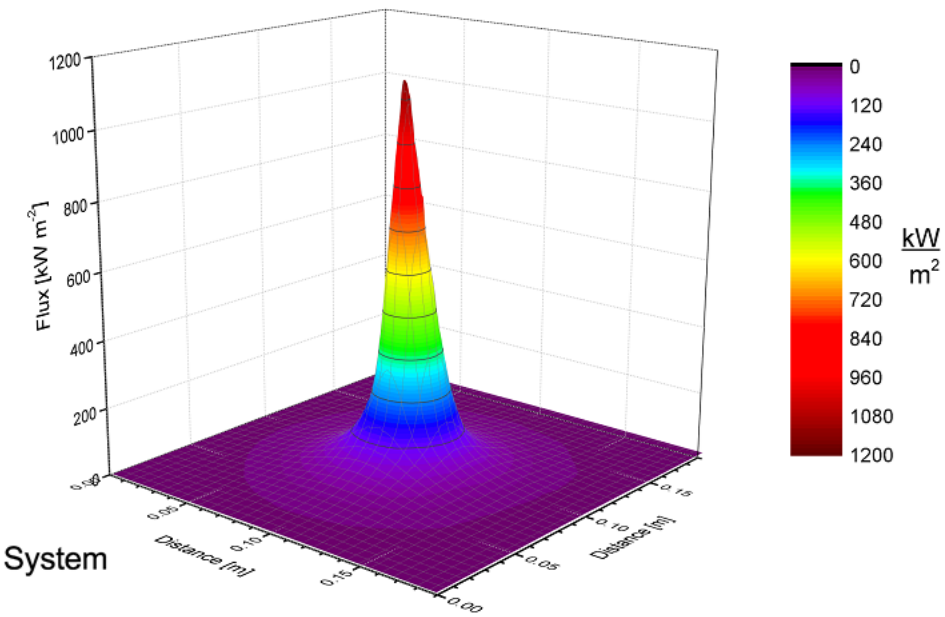
Solar Simulator:
4 kW_{el} short-arc Xe lamp
elliptical reflector

Fluidized Bed
0.78 m square cross section
0.6 m height

SiC [127 µm]

APH = Air Pre-Heater
BGS = Bubble Generation System
FG = Fluidizing Gas
MFC = Mass Flow Controller
PT = Pressure Transducer
TC = Thermocouple
WB = Windbox

Solar Simulator Heat Flux Distribution

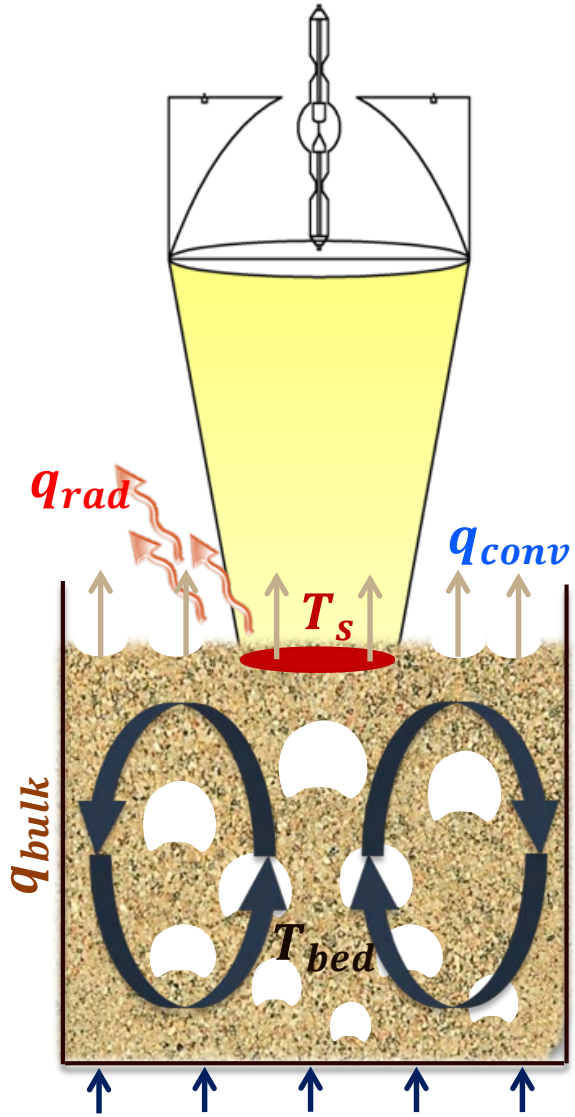


Q_{peak} : 1100 kW m^{-2}, d=20 cm
W_{tot}= 1200 W

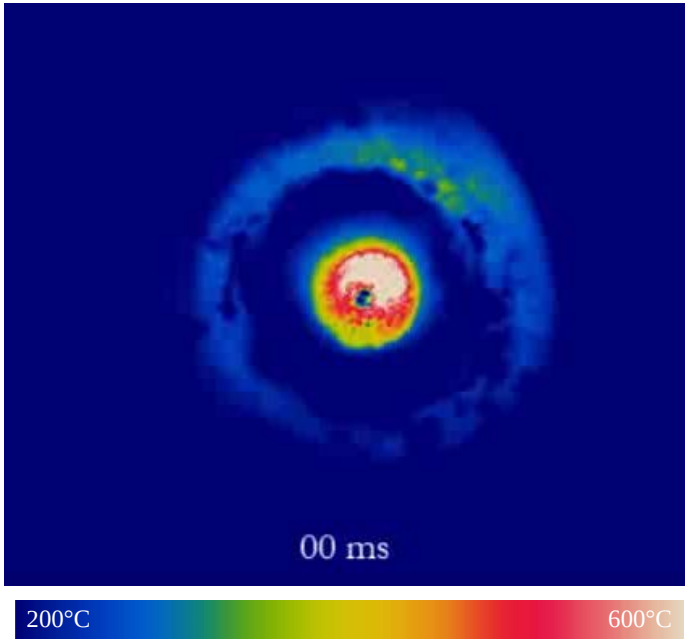
The BGS was optimized to generate bubbles at 1 Hz and with a mean diameter of 0.065 m.

Tregambi et al., Solar Energy (2016)

THERMAL MAPS AND COMPARTMENTAL MODEL



Nozzle-surface gap: 0.09 m

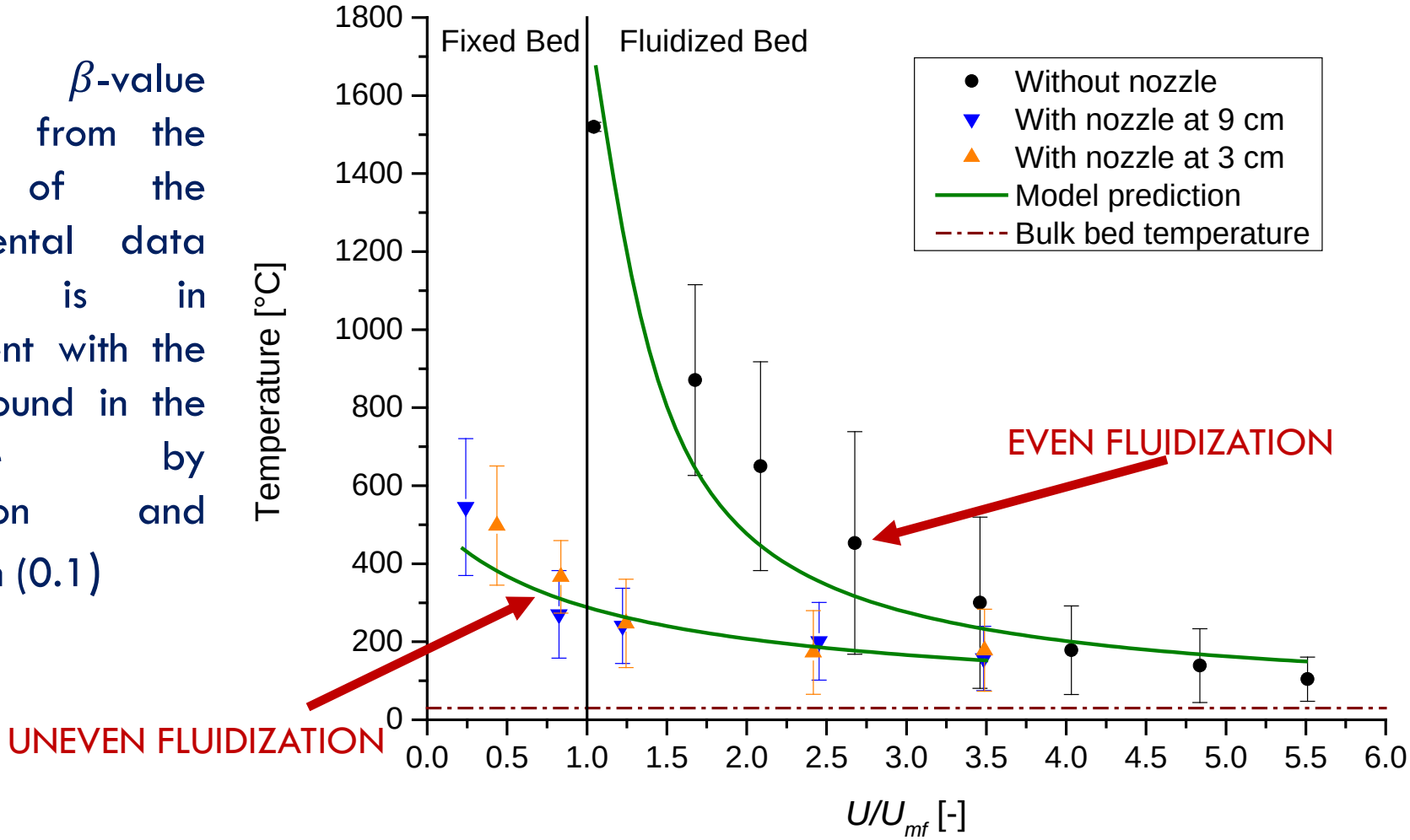


$$\alpha q = \varepsilon\sigma T_s^4 + \rho U \overline{c_p}(T_s - T_{bed}) + \beta\rho_s(1-\varepsilon_{mf})(U - U_{mf})\overline{c_{ps}}(T_s - T_{bed})$$

Tregambi et al., Solar Energy (2016)

BED SURFACE OVERTEMPERATURE

The β-value obtained from the fitting of the experimental data (0.071) is in agreement with the values found in the literature by Pemberton and Davidson (0.1)



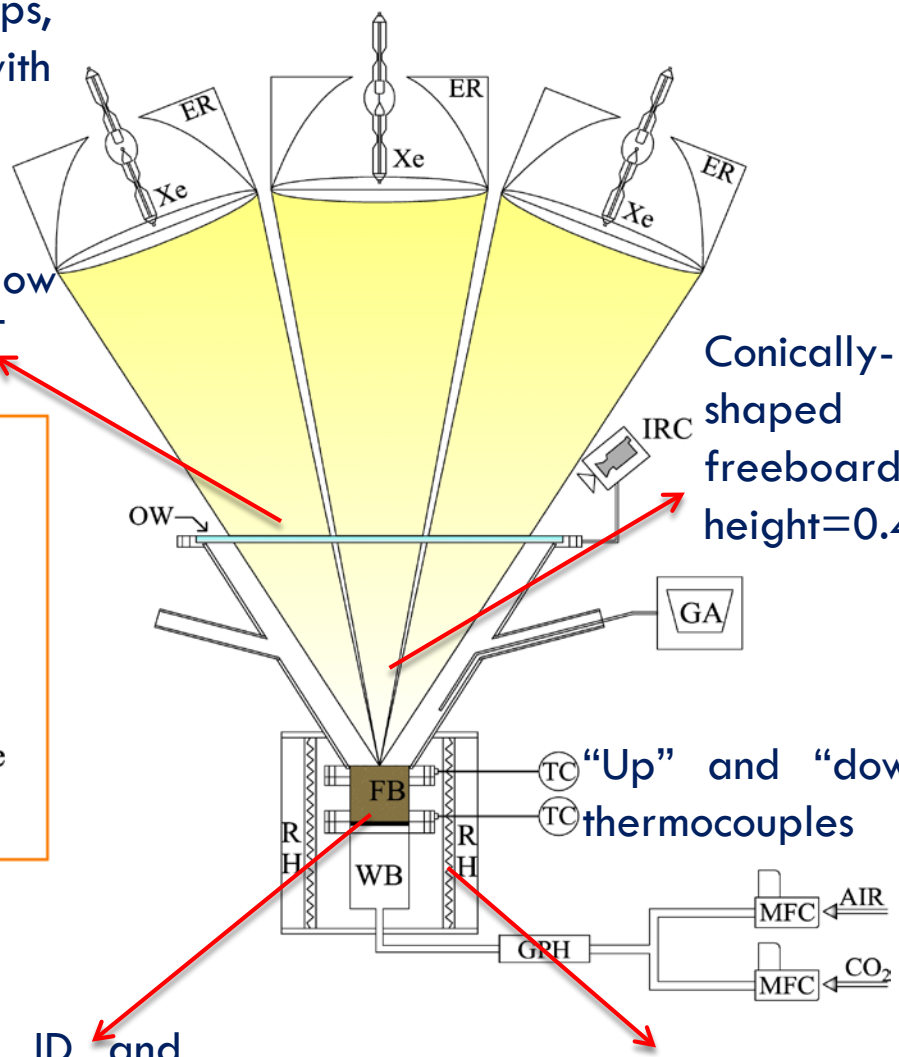
Tregambi et al., Solar Energy (2016)

DIRECTLY IRRADIATED FLUIDIZED BED REACTOR

3 short-arc Xe lamps, 4 kWel each, with elliptical reflectors

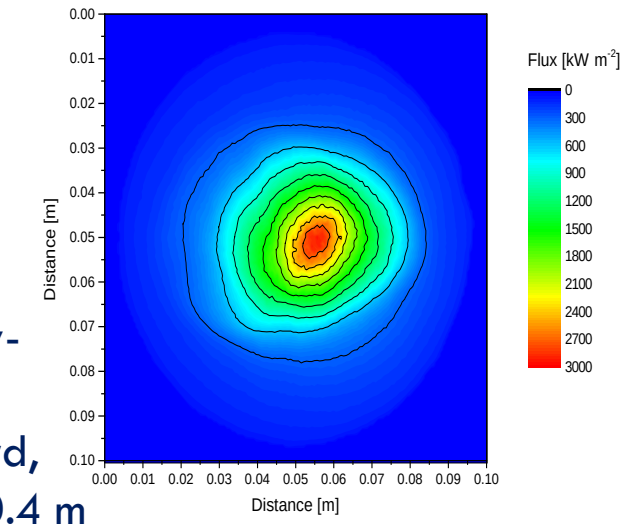
Transparent window resistant to high T

Conically-shaped freeboard, height=0.4 m



ER:	Elliptical Reflector
FB:	Fluidized Bed
GA:	Gas Analyzer
GPH:	Gas Preheater
IRC:	Infrared Camera
MFC:	Mass-flow Controller
OW:	Optical Window
RH:	Radiant Heaters
TC:	K-type Thermocouple
WB:	Windbox
Xe:	Short-arc Xe-lamp

"Up" and "down" thermocouples



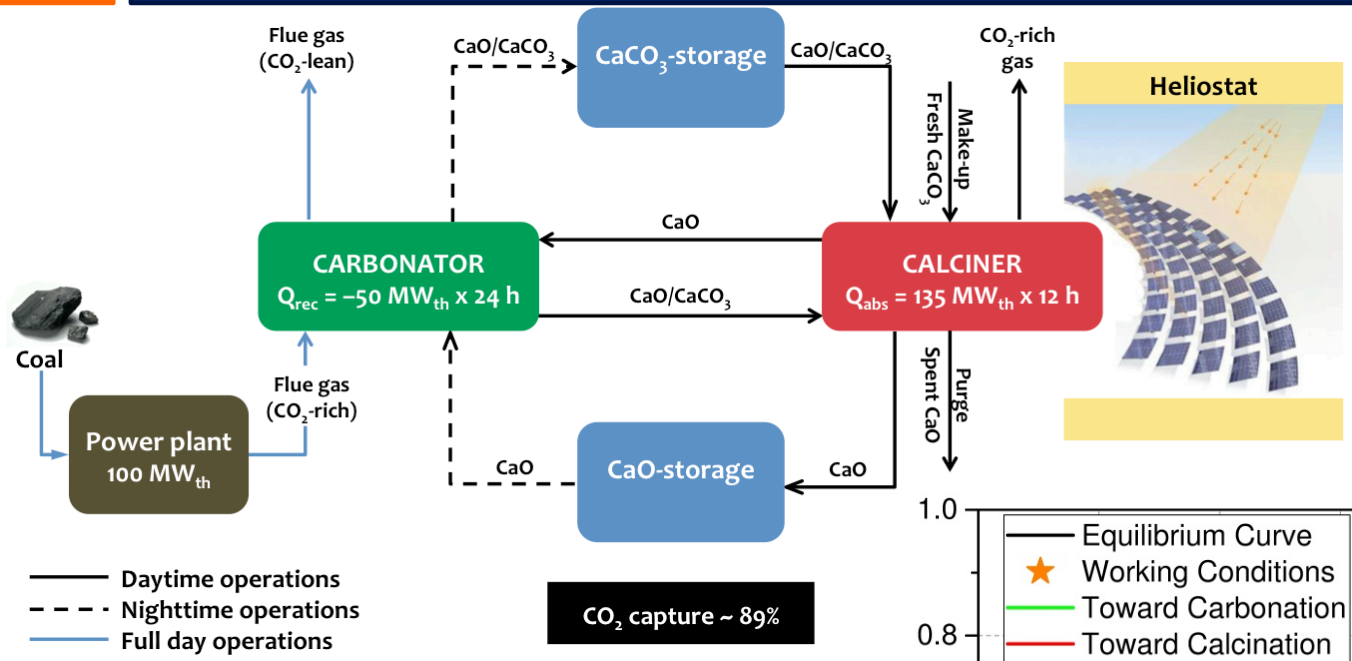
Thermal characterization according to a a previous study (*Sol. Energy 2016*): peak flux=3000 kW m^{-2}, average flux 390 kW m^{-2}, irradiated power=3.2 kW

FB with ID and height=0.1 m

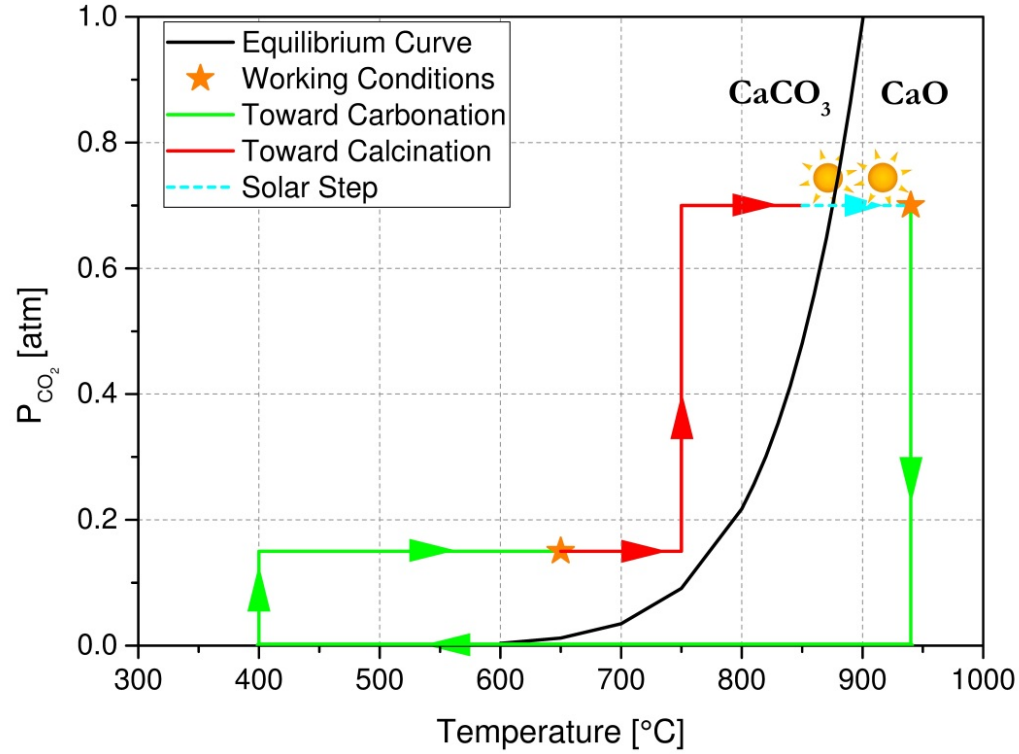
Radiant heaters

Tregambi et al., SolarPACES (2016)

SOLAR CALCIUM LOOPING

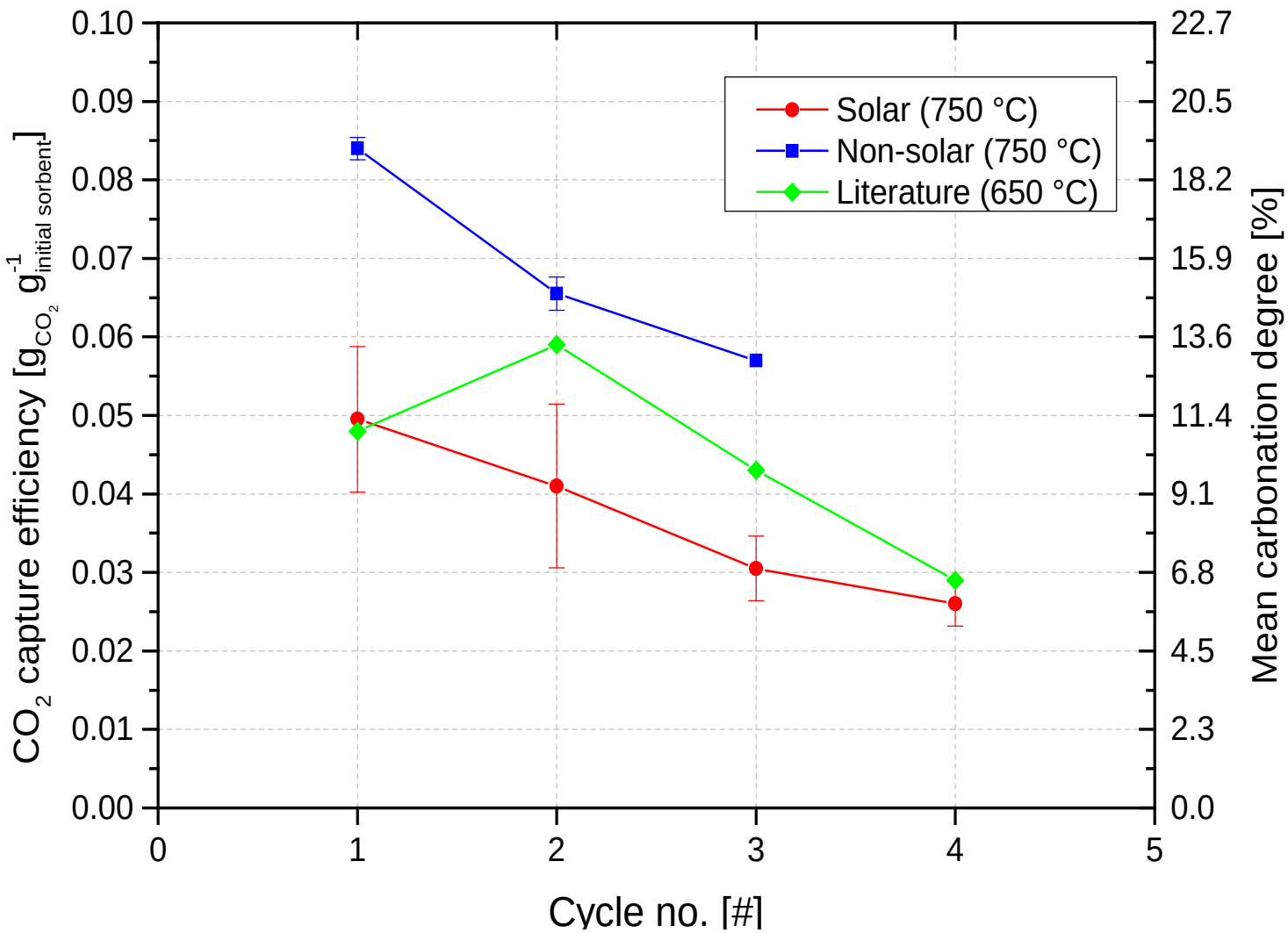


Tregambi et al., Solar Energy (2015)



Tregambi et al., SolarPACES (2016)

CO_2 CAPTURE EFFICIENCY



Tregambi et al., SolarPACES (2016)

QUESTIONS?