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DYNAMIC MODEL OF A PARTICLE/SCO_2 HEAT EXCHANGER FOR TRANSIENT ANALYSIS AND CONTROL

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OUTLINE

1. Introduction and objectives
2. Numerical model
3. Sensitivity analysis
4. Transient analysis
5. Control strategies
6. Conclusions

OUTLINE

1. Introduction and objectives

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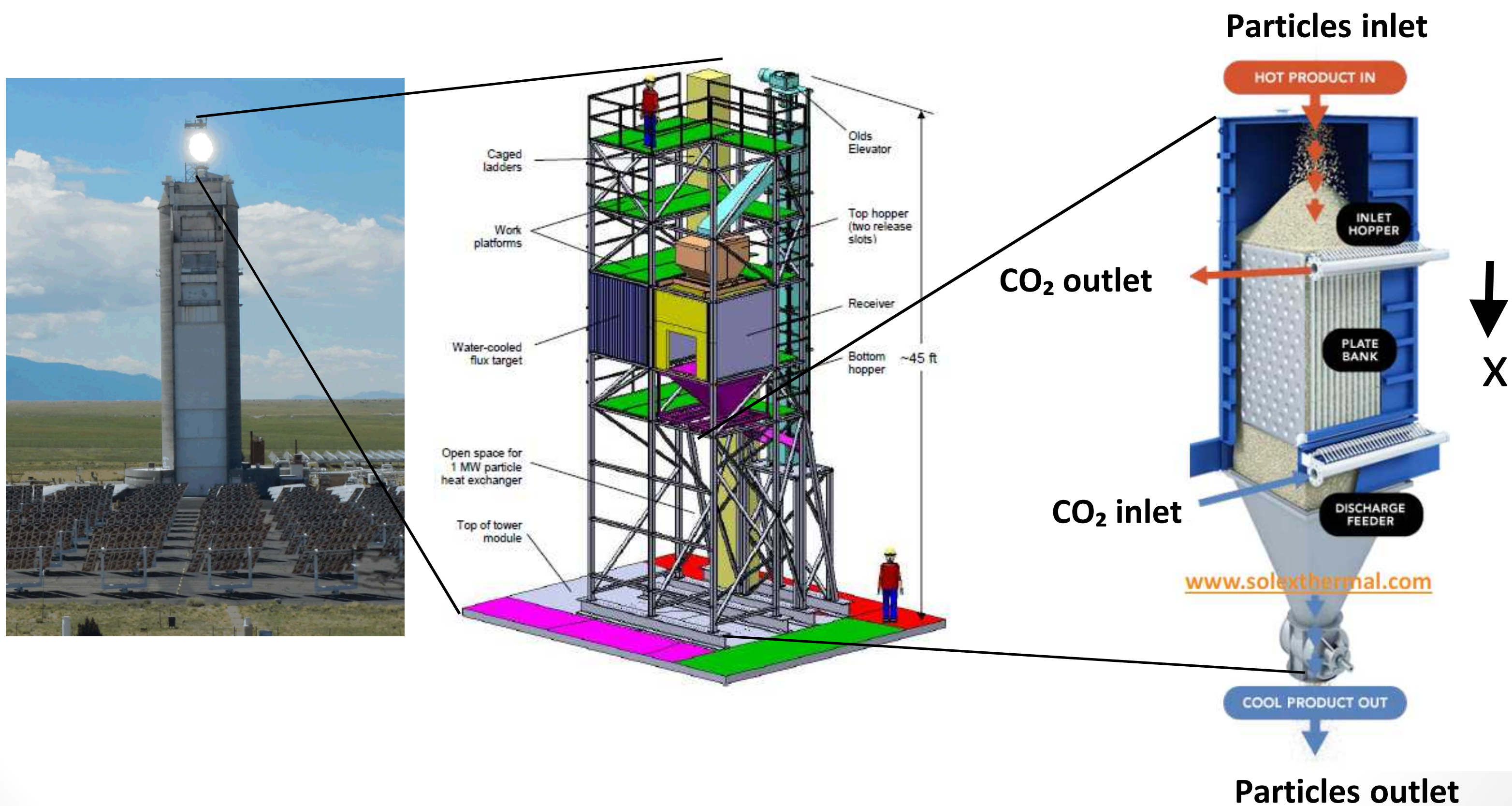
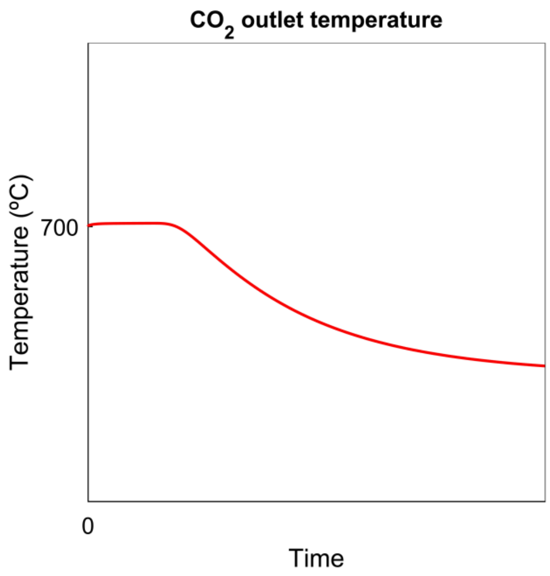
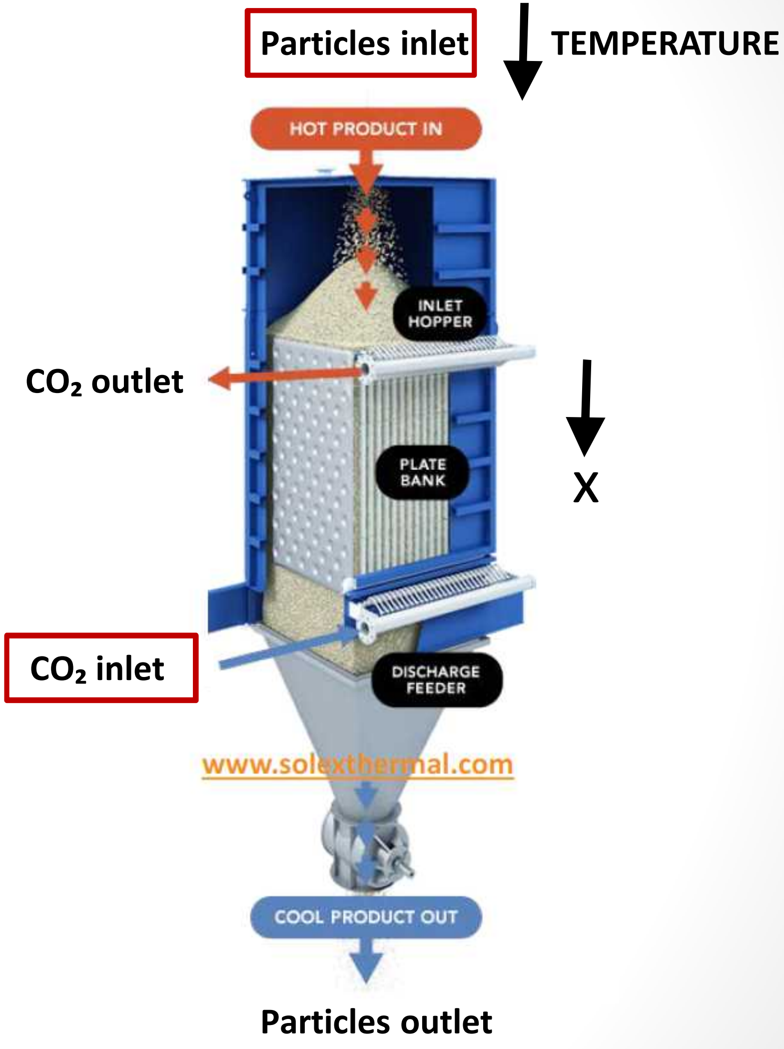
- Solid particle receivers integrated with sCO_2 power cycles: ↑T ↑ efficiency
- The design of particle-to- sCO_2 is necessary ➡ Shell and plate moving packed bed HX



1. Introduction and objectives





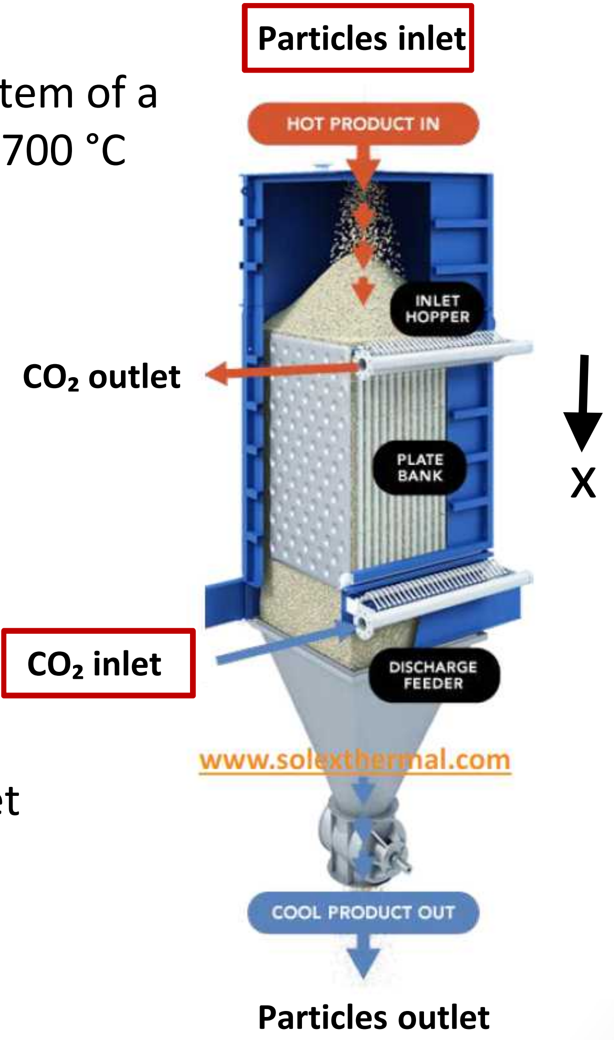
1. Introduction and objectives

- Main objective: to design the control system of a particle-to-sCO_2 HX to maintain $T_{out,sCO2}$ =700 °C

Steps:

1. To study the transient response of the HX in presence of inlet conditions deviations from the design point

2. To investigate the control system to minimize both particles and sCO_2 outlet temperature deviations



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2. Numerical model

3. 1D transient conservation of energy equations

Particles

$$\rho_s \cdot c_{p,s} \cdot \frac{\partial T_s}{\partial t} = -\rho_s \cdot c_{p,s} \cdot u_s \cdot \frac{\partial T_s}{\partial x} + \frac{2 \cdot \overline{h_{sw}}}{hc_s} \cdot (T_w - T_s)$$

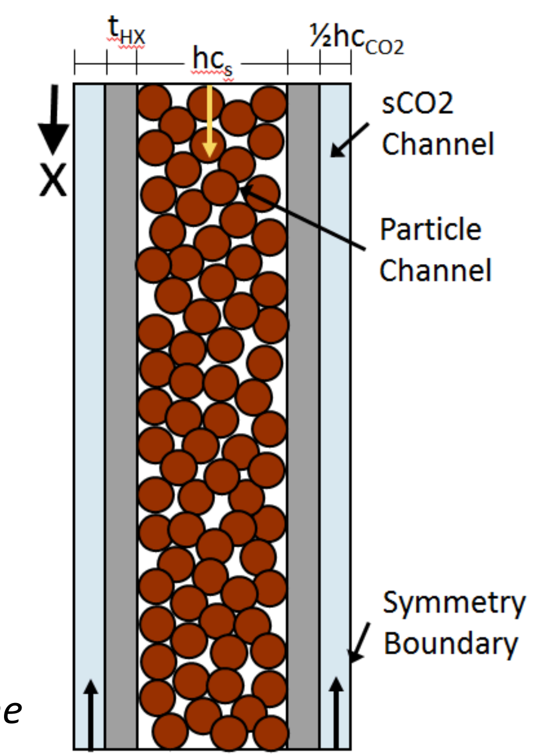
sCO_2

$$\rho_{CO_2} \cdot c_{p,CO_2} \cdot \frac{\partial T_{CO_2}}{\partial t} = -\rho_s \cdot c_{p,s} \cdot u_s \cdot \frac{\partial T_{CO_2}}{\partial x} + \frac{2 \cdot h_{CO_2}}{hc_{CO_2}} \cdot (T_w - T_{CO_2})$$

Wall

$$\rho_w \cdot c_{p,w} \cdot \frac{\partial T_w}{\partial t} = \frac{\overline{h_{sw}}}{t_{HX}} \cdot (T_s - T_w) + \frac{h_{CO_2}}{t_{HX}} \cdot (T_{CO_2} - T_w)$$

- $\overline{h_{sw}}$ is considered to be 150 W/(m²·K) in accordance to previous 2D steady state calculations (*"Heat transfer models of moving packed-bed particle-to-sCO2 heat exchangers", Albrecht, K., Ho, Clifford, Proceedings of the ASME 2017 Power and Energy Conference*)
- h_{CO_2} according to Gnielinsky correlation
- Implicit method MATLAB



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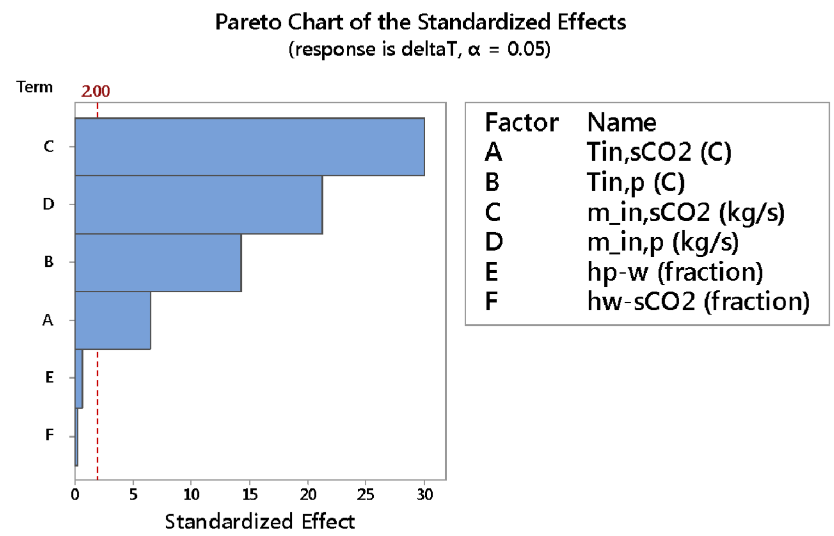
3. Sensitivity analysis

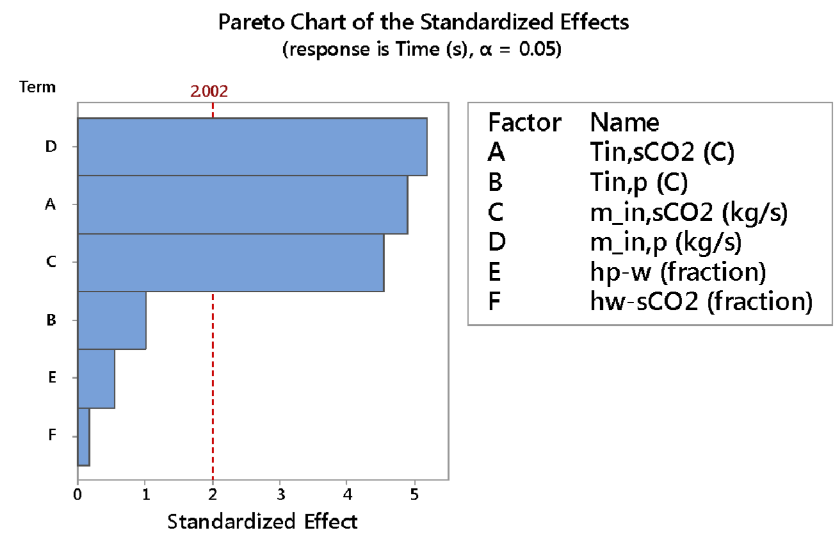
4. Sensitivity analysis – design of experiments

- DoE: which variables have a strong influence on HX response?
- Analysis of variance (ANOVA)
  - Independent variables:
    - Inlet conditions: $T_{in,sCO2}$, $T_{in,p}$, m_{sCO2} , m_p (changes during plant operation)
    - Heat transfer coefficients: $\overline{h_{sw}}$ and h_{sCO2} (correlations uncertainty)
  - Dependent variables:
    - Time to reach equilibrium
    - $\Delta T = T_{out,sCO2} - 700°C$

	Design point	Deviations	Final value
Particle inlet temperature ($T_{in,p}$) (°C)	775	↓ 50	725
sCO2 inlet temperature ($T_{in,sCO2}$) (°C)	550	↓ 50	500
sCO2 mass flow rate (m_{sCO2}) (kg/s)	0.0267	↓ 50%	0.0133
Particle mass flow rate (m_p) (kg/s)	0.02	↓50%	0.01
Average particle-wall convection coeff ($\overline{h_{sw}}$) (W/(m²·K))	150	↓10%	135
sCO2-wall convection coeff (h_{sCO2}) (W/(m²·K))	600	↓10%	540

4. Sensitivity analysis results





- Conclusions:
  - A 10% change in $\overline{h_{sw}}$ and h_{sCO2} does not strongly affect the HX response
  - HX response is strongly affected by changes in inlet temperature and mass flow rates of sCO2 and particles

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4. Transient analysis

4. Transient analysis

- 6 different cases varying $T_{in,sCO2}$, $T_{in,p}$, m_{sCO2} along the time

Design point					
$T_{in,p}$ (°C)	$T_{in,sCO2}$ (°C)	m_{CO2}(kg/s)	m_p (kg/s)	$(\overline{h_{sw}})$ (W/(m²·K))	h_{sCO2}(W/(m²·K))
775	550	0.0267	0.02	150	600

Case	$T_{in,p}$ (°C)		$T_{in,sCO2}$ (°C)		m_{sCO2} (kg/s)	
	Deviation	Value	Deviation	Value	Deviation	Value
1	↓50 °C	725	↓50 °C	500	↓50 %	0.0133
2	↓25 °C	750	=	550	↓50 %	0.0133
3	=	775	↓50 °C	500	↓50 %	0.0133
4	=	775	=	550	↓50 %	0.0133
5	↓25 °C	750	↓50 °C	500	=	0.0267
6	=	775	↓50 °C	500	=	0.0267

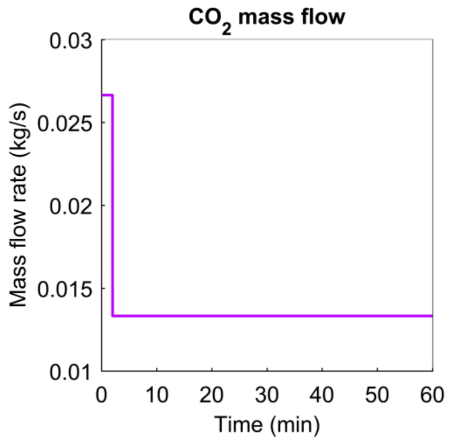
- 2 different change rates:
  - Instantaneous
  - Linearly decreasing in 30 min

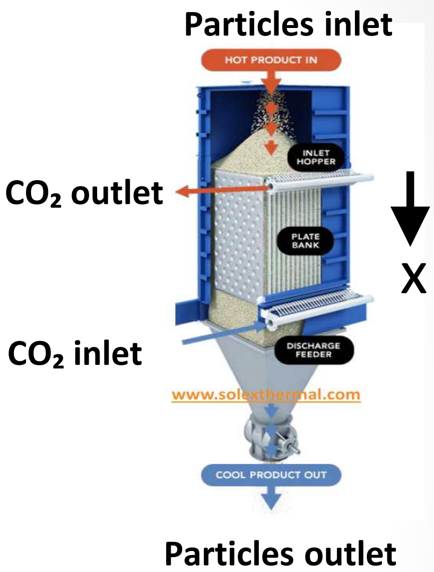
Transient results with change in sCO_2 temperature and mass flow rate

Inlet conditions

$T_{in,p}$ =775 °C
$T_{in,sCO2}$ =500°C (↓50 °C)
m_{sCO2}=0.0133 kg/s (↓50 %)

Step change ———





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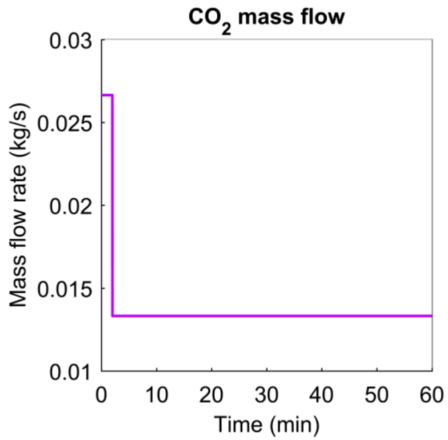

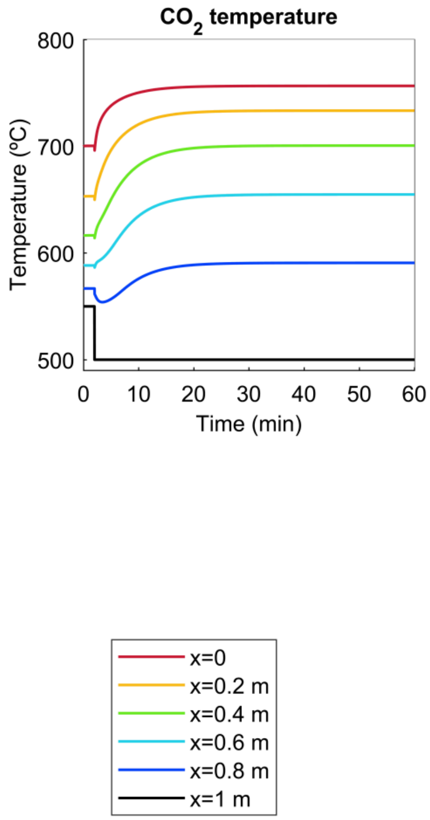

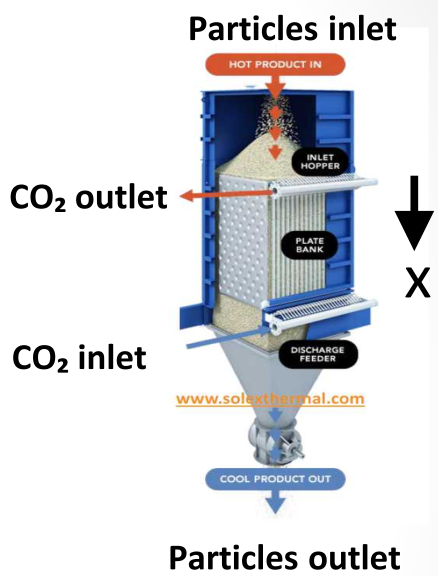

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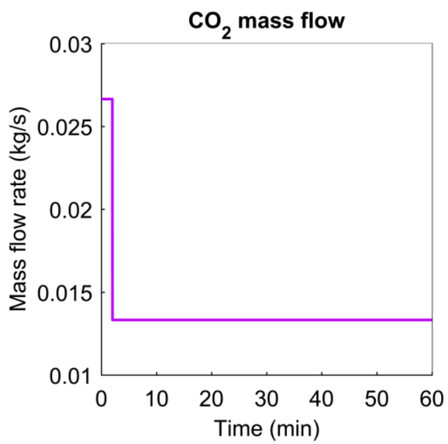

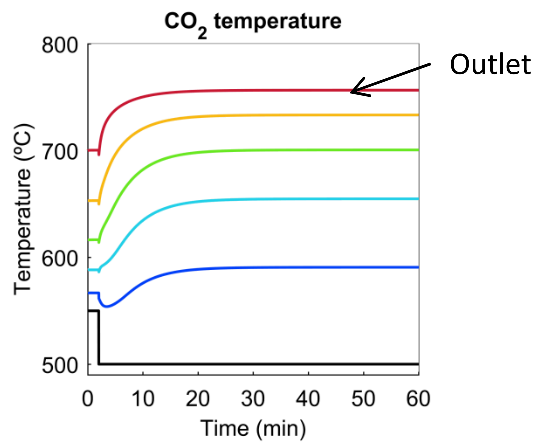

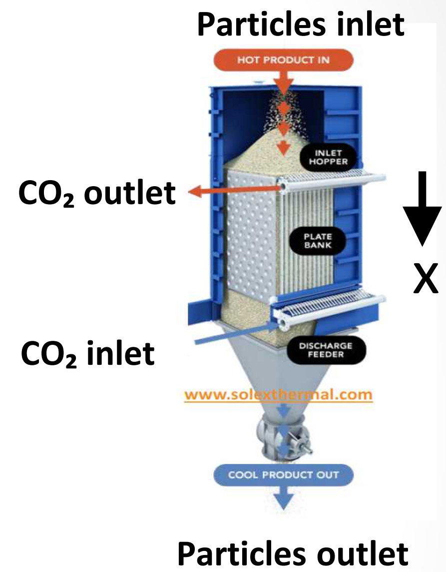

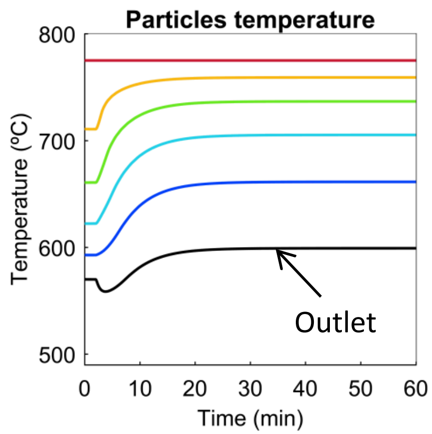

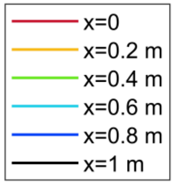

Temperature deviations:
30 °C in $T_{out,p}$
60 °C in $T_{out,sCO2}$

A control system is necessary

Transient results with change in sCO_2 temperature and mass flow

Inlet conditions

$T_{in,p}$ =775 °C
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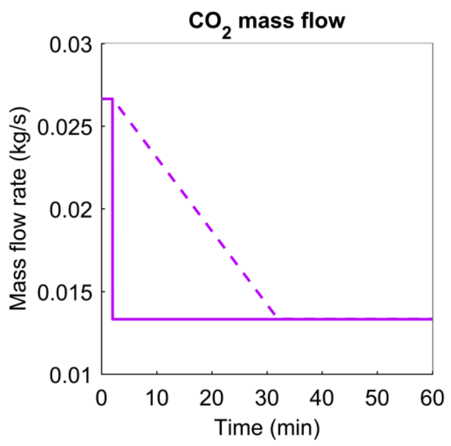
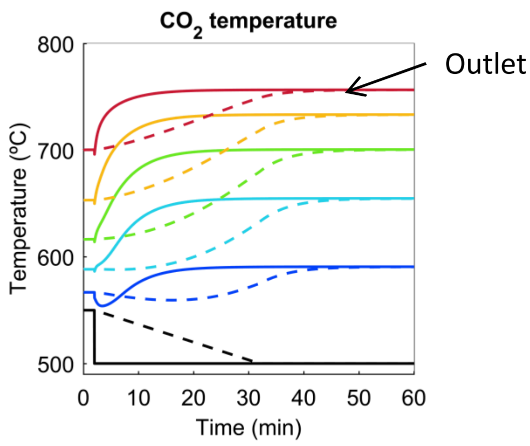
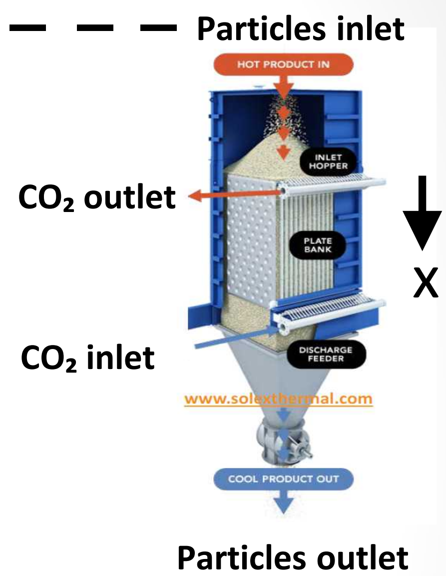
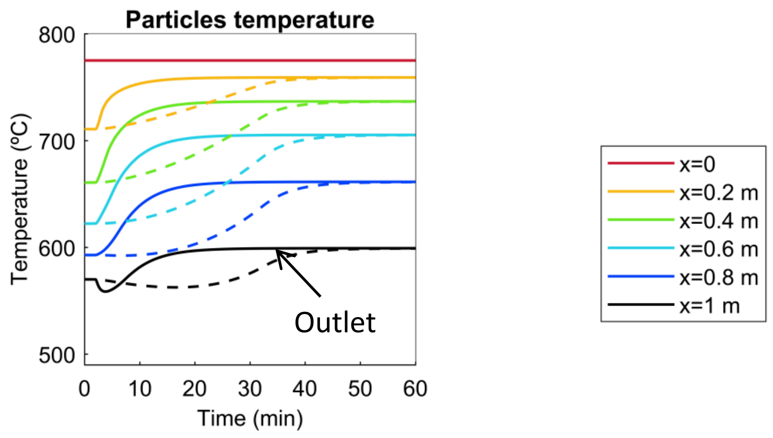
Step change ———
30 min change — — —









Temperature deviations:
30 °C in $T_{out,p}$
60 °C in $T_{out,sCO2}$

⇩

A control system is necessary

OUTLINE

5. Control strategies

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- Goal: to maintain both $T_{out,sCO2}$ and $T_{out,p}$ deviations from the desired values (700 °C and 570 °C respectively) below 1°C when modifying **$T_{in,sCO2}$, $T_{in,p}$, m_{sCO2}** (cases 1-6)

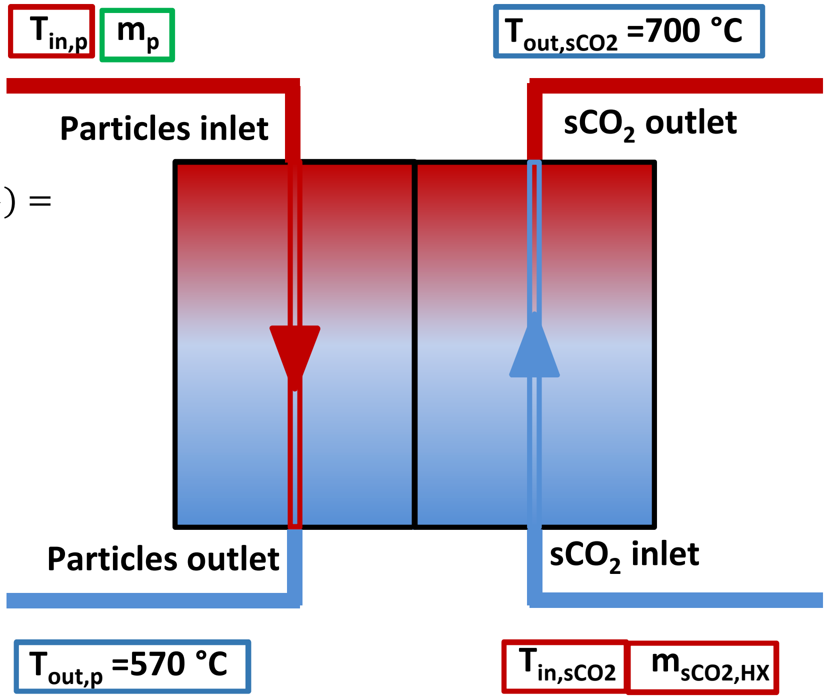
- Steady state equations

1) Heat exchanger energy balance

$$m_{sCO2,HX} \cdot c_{p,sCO2} \cdot (T_{out,sCO2,HX} - T_{in,sCO2,HX}) = m_p \cdot c_{p,p} \cdot (T_{in,p} - T_{out,p})$$

2) ΔT mean log equation

$$m_p \cdot c_{p,p} \cdot (T_{in,p} - T_{out,p}) = U \cdot A \cdot \Delta T_{lm}$$



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$$m_{sCO2,HX} \cdot c_{p,sCO2} \cdot (T_{out,sCO2,HX} - T_{in,sCO2,HX}) = m_p \cdot c_{p,p} \cdot (T_{in,p} - T_{out,p})$$

2) ΔT mean log equation

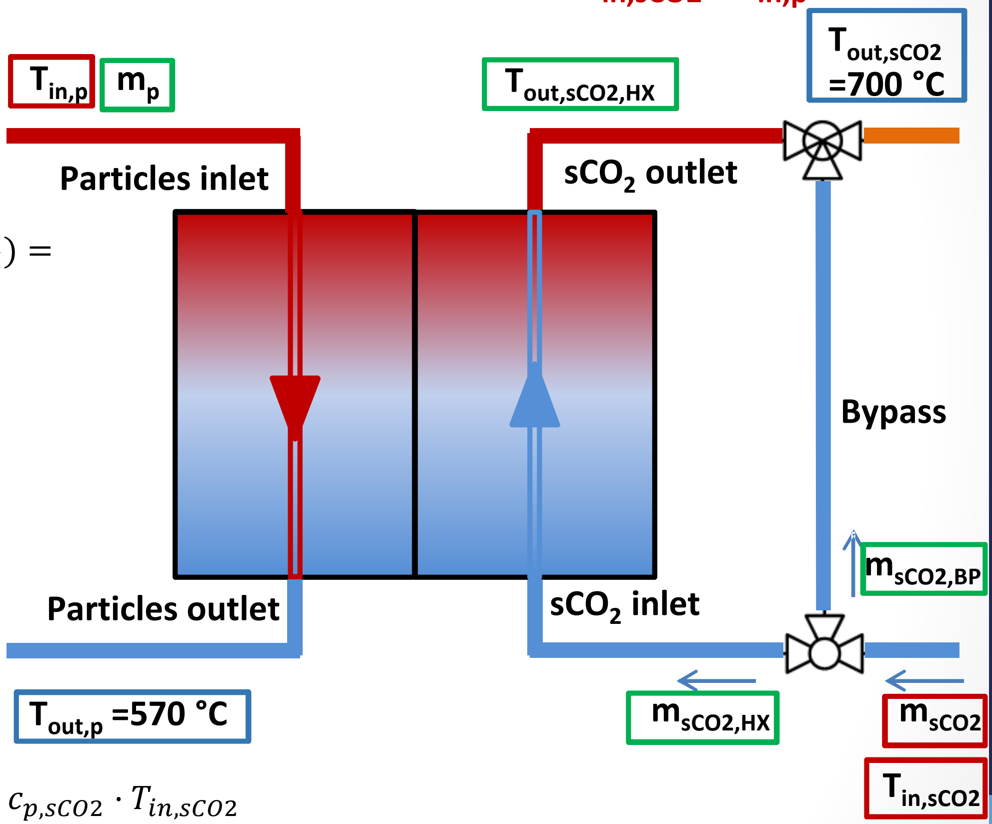
$$m_p \cdot c_{p,p} \cdot (T_{in,p} - T_{out,p}) = U \cdot A \cdot \Delta T_{lm}$$

3) Bypass mass balance

$$m_{sCO2} = m_{sCO2,BP} + m_{sCO2,HX}$$

4) Bypass energy balance

$$m_{sCO2} \cdot c_{p,sCO2} \cdot T_{out,sCO2} = m_{sCO2,HX} \cdot c_{p,sCO2} \cdot T_{out,sCO2,HX} + m_{sCO2,BP} \cdot c_{p,sCO2} \cdot T_{in,sCO2}$$



4 equations-4 unknown variables: $m_{sCO2,HX}$, $m_{sCO2,BP}$, m_p, $T_{out,sCO2,HX}$

5. Control strategies

- Steady state: for the inlet conditions of the 6 cases studied, $m_{sCO2,HX}$ and m_p can be calculated to obtain the desired temperatures

- Transient solution: steady state solution + proportional correction

$$m_{sCO2,HX}(t) = m_{sCO2,HX,ste}(t) - K_{sCO2} \cdot (T_{out,sCO2}(t) - 700)$$

$$m_p(t) = m_{p,ste}(t) - K_p \cdot (T_{out,p}(t) - 570)$$

Proportional correction:

- To reduce $T_{out,sCO2}$ and $T_{out,p}$ deviations from the desired value
- K_{sCO2} and K_p depends on the **$T_{in,sCO2}$, $T_{in,p}$, m_{sCO2}** change rate

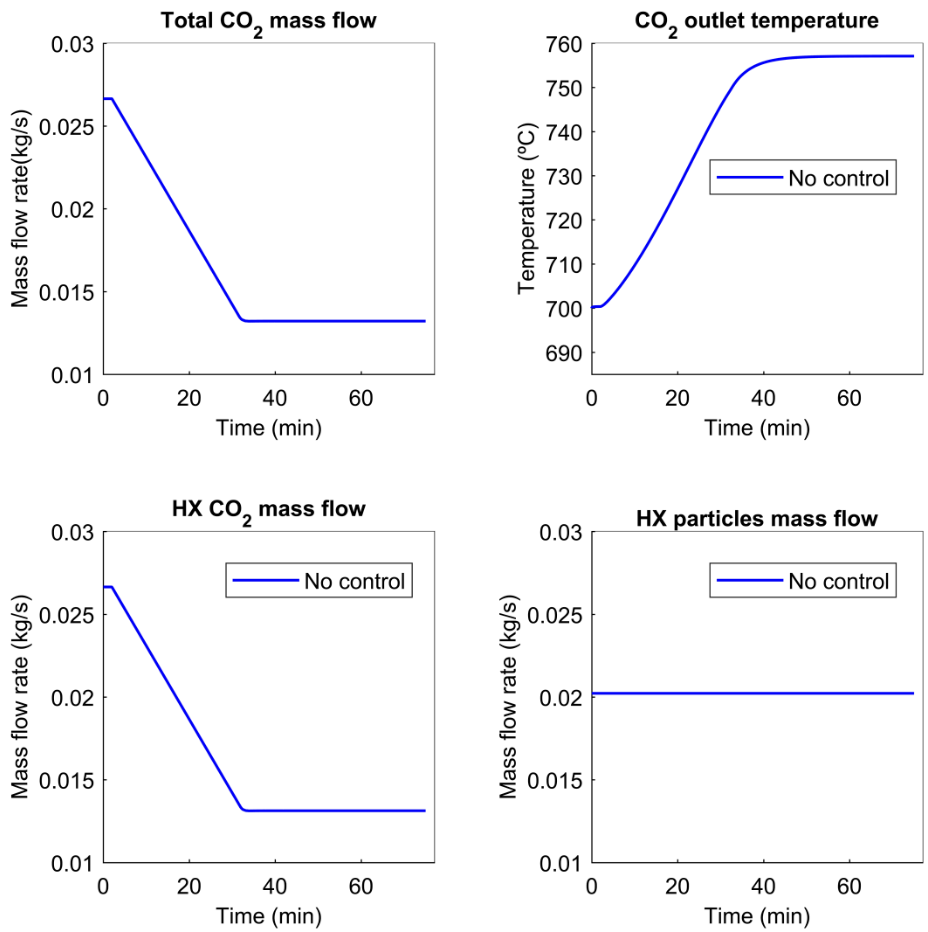
Case	K_{sCO2}			K_p		
	Step	30 min	60 min	Step	30 min	60 min
1	1.00E-04	5.00E-04	1.00E-04	0.02	5.00E-04	1.00E-04
2	1.00E-04	0	0	1.00E-04	0	0
3	1.00E-04	1.00E-04	1.00E-04	0.1	7.00E-03	7.00E-03
4	1.00E-04	1.00E-04	1.00E-04	0.1	1.50E-04	1.50E-04
5	1.00E-04	1.00E-04	1.00E-04	0.02	7.00E-03	7.00E-03
6	1.00E-04	1.00E-04	1.00E-04	0.02	7.00E-03	7.00E-03

Control results with change in sCO_2 temperature and mass flow in 30 min

Inlet conditions

$T_{in,p}$ =775 °C
$T_{in,sCO2}$ =500 °C (↓50 °C)
m_{sCO2}=0.0133 kg/s (↓50 %)

No control $\Delta T_{out,sCO2}$ =60 °C



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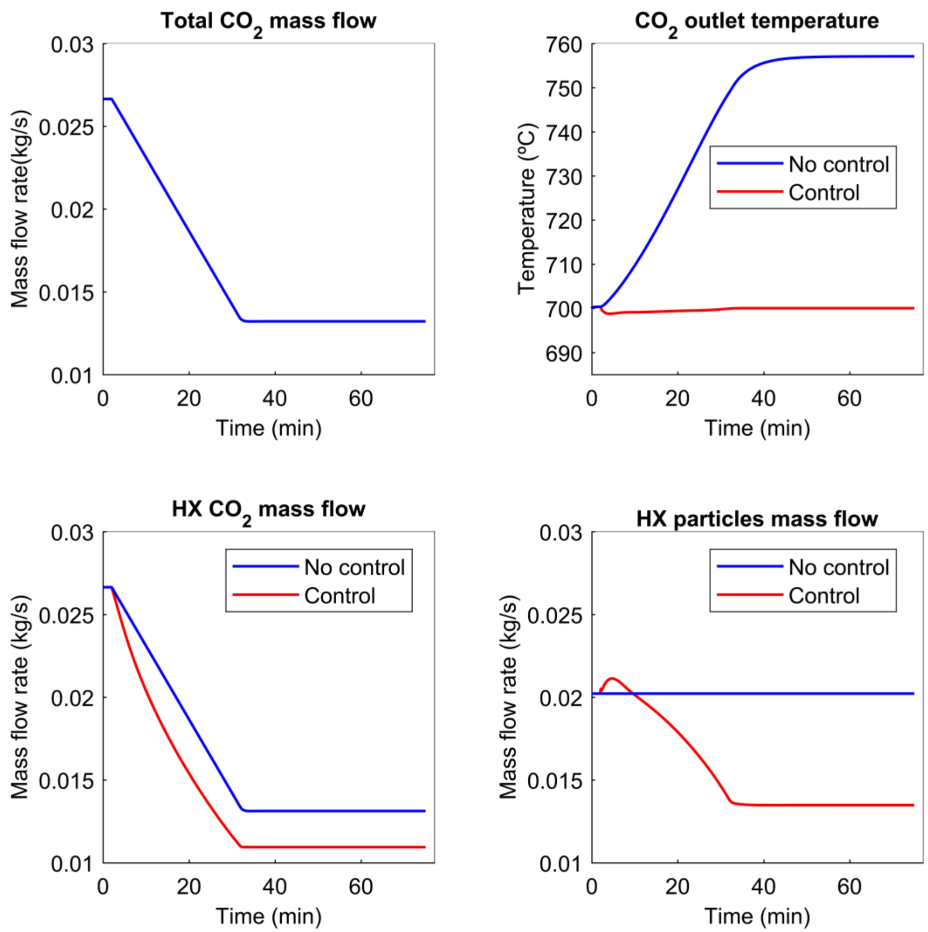
No control $\Delta T_{out,sCO2}$ =60 °C

Control $\Delta T_{out,sCO2}$ =1 °C



OUTLINE

6. Conclusions

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- The transient response of moving packed bed particles-to-sCO2 HX in presence of inlet conditions deviations was analyzed

- A control system is needed to maintain the desired outlet temperatures during transient response

- The control system is based on installing a bypass in the sCO2 side. Particles and sCO2 mass flow rates through the HX are adjusted to maintain the desired outlet temperatures

- The control system developed maintains outlet temperature deviations below 1C

Acknowledgements

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Thank you for your attention