Dynamic modeling and transient analysis of a molten salt heated recompression supercritical CO_2 Brayton cycle

For the 6th International Supercritical CO_2 Power Cycles Symposium

Jinyi ZHANG

EDF R&D China

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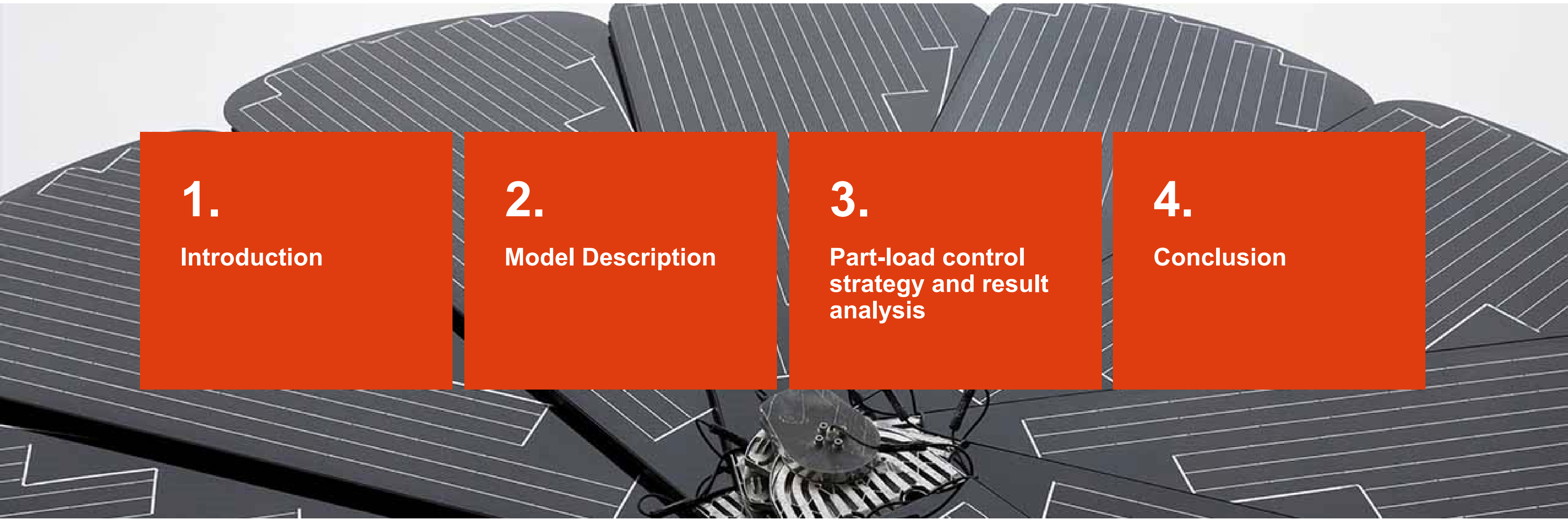
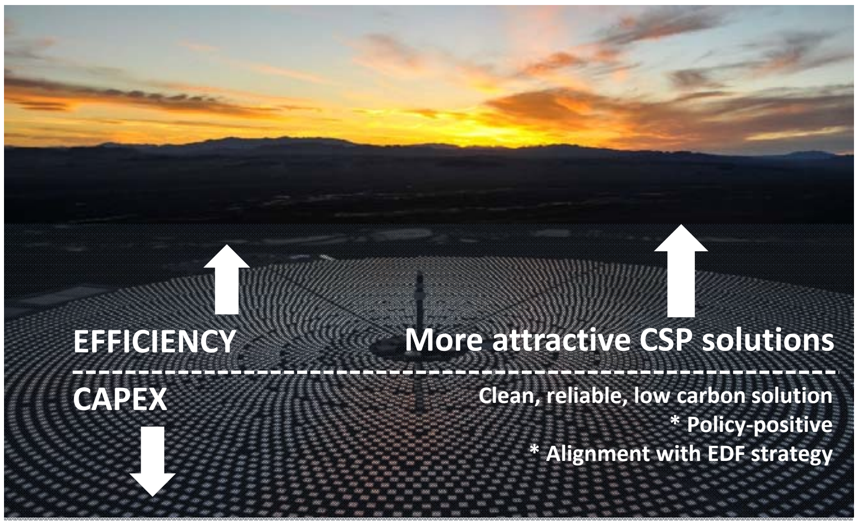
OUTLINE



1. Introduction
2. Model Description
3. Part-load control strategy and result analysis
4. Conclusion

Supercritical CO_2 Cycle + CSP



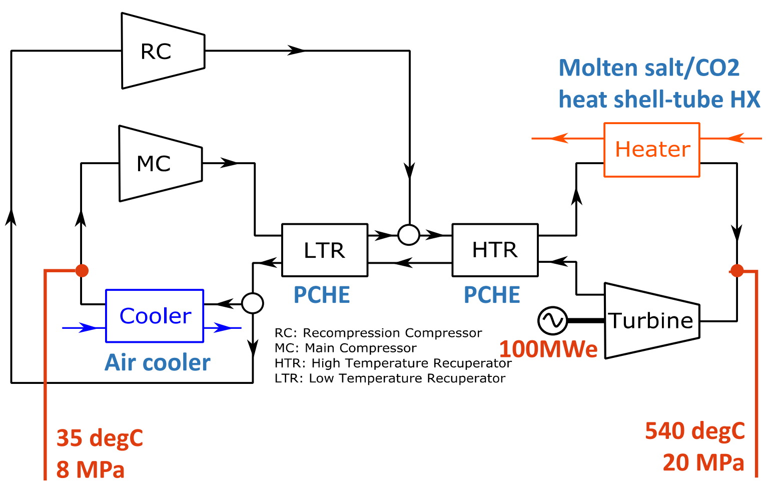
- SCO_2, together with high temperature (> 500 ℃) molten salt CSP solutions, could achieve higher efficiency than steam solutions.
- The size of CSP plant is between 50MWe and 150MWe, which is suitable for the first industrial demonstration of cycle.
- Recompression cycle is taken for a preliminary cycle dynamics study, because this is the most studied layout with a good balance between complexity and efficiency.

Design

- **100MWe : average size of CSP plant**
- **Molten salt heated recompression cycle: compatible with current CSP**

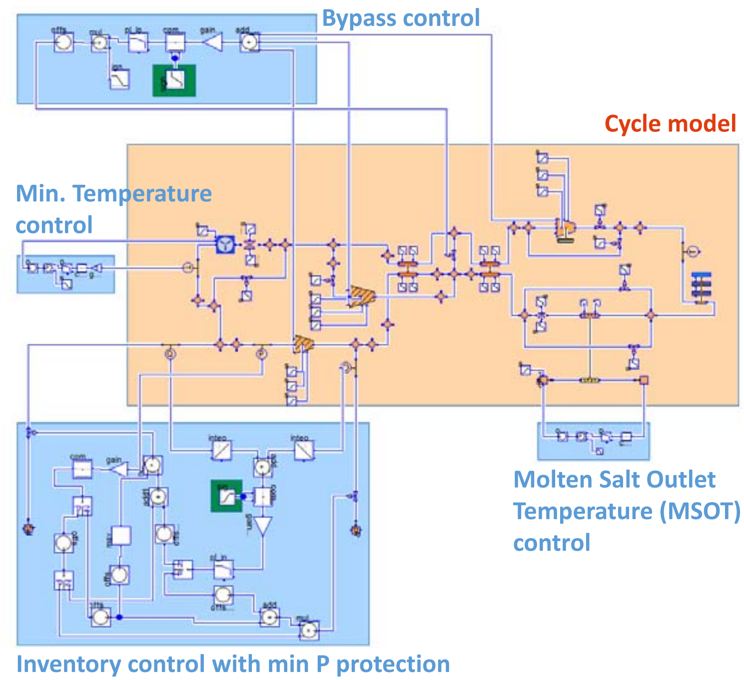
Dynamic Modeling for Control System Design

Recompression layout



DYMOLA

Predesign toolbox



Turbo-machinery performance model

Energy balance → **Pre-design** → **Off-design** → **Non-dimensionalize** → **DYMOLA**

Energy balance
- ➢ Boundary conditions

Can be get by steady-state simulation.

Turbo-machinery pre-design tools
- ➢ Geometry

Based on the mean-line design tool self-developed.

Turbo-machinery off-design model
- ➢ Performance map (Q dependant)

Using off-design model to get the performance map.

Non-dimensionalization
- ➢ post-processing

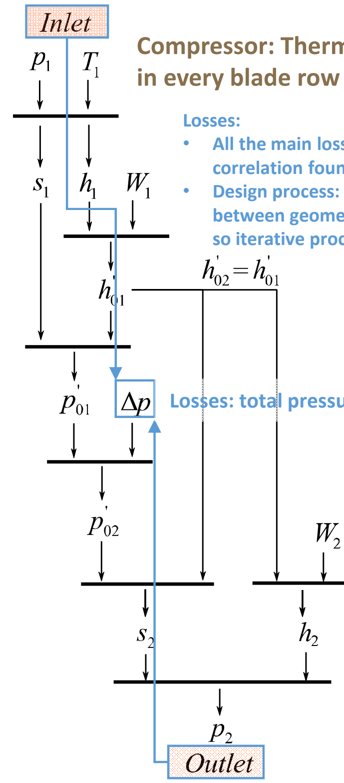
The final obtained curve will be imported in DYMOLA.

DYMOLA
- ➢ Simulation

Turbo-machinery is modelled based on the non-dimensionalized curve.

A realistic model which predicts performance (isentropic efficiency and compression ratio) depending on:

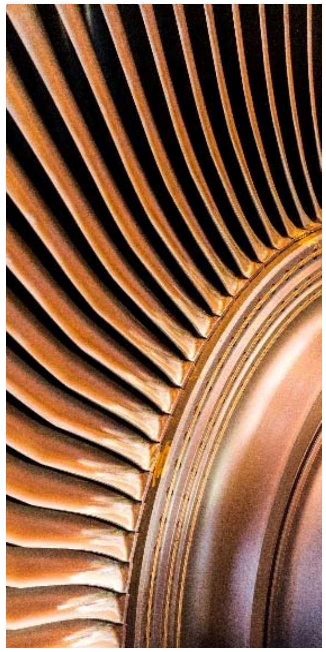
Inlet conditions
Mass flow rate
Rotation speed



Compressor: Thermodynamic calculation in every blade row

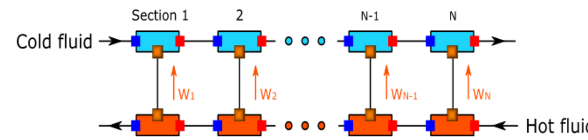
Losses:
- All the main losses are implemented with correlation found in the open literature.
- Design process: Cross-dependency between geometry and outlet conditions, so iterative procedure is applied

Losses: total pressure losses



Model Description

Heat Exchanger Modeling



Energy balance → **Pre-design** → **Modeling** → **DYMOLA**

Energy balance

➢ Boundary conditions

Can be get by steady-state simulation.

Pre-design

➢ Geometry

Based on pre-design tools.

Off-design model

➢ dymola Model

Off-design modeling in Dymola

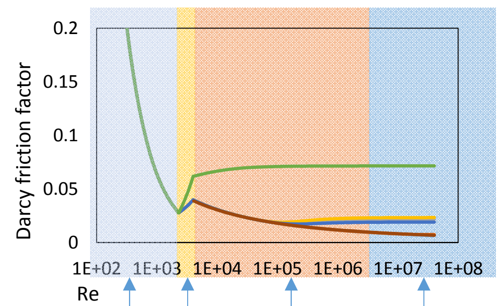
DYMOLA

➢ Simulation

The implemented model will be simulated in Dymola.

A realistic model which predicts on-design and off-design performance of heat exchanger

Pressure drop: Darcy friction factor



laminar

$$f_D = \frac{64}{Re}$$

Critical

Interpolation

Transition

Turbulence

$$\frac{1}{\sqrt{f_D}} = -2\log_{10}\left(\frac{2.51}{Re\sqrt{f_D}} + \frac{\varepsilon}{3.7D_h}\exp\left(-j\frac{5.66}{Re\sqrt{f_D}}\frac{r}{\varepsilon}\right)\right)$$

Heat transfer : Heat transfer coefficient

Laminar flow : Interpolation using following table [Hesselgreaves 2001]

x^*	$Nu_{x,H1}$ D	$Nu_{x,H1}$ D	x^*	$Nu_{x,H1}$ D	$Nu_{x,H1}$ D
0.000458	17.71	17.43	0.0279	4.767	4.339
0.000954	13.72	13.41	0.0351	4.562	4.037
0.00149	11.80	11.37	0.0442	4.429	3.830
0.00208	10.55	10.08	0.0552	4.276	3.686
0.00271	9.605	9.141	0.0686	4.217	3.543
0.00375	8.475	8.127	0.0849	4.156	3.425
0.00493	7.723	7.375	0.105	4.124	3.330
0.00627	7.137	6.788	0.130	4.118	3.265
0.00777	6.556	6.312	0.159	4.108	3.208
0.00946	6.300	5.912	0.196	—	3.171
0.0128	5.821	5.368	0.241	—	3.161
0.0168	5.396	4.935	0.261	—	3.160
0.0217	5.077	4.579	∞	4.089	3.160

Turbulent flow : Gnielinski Correlation

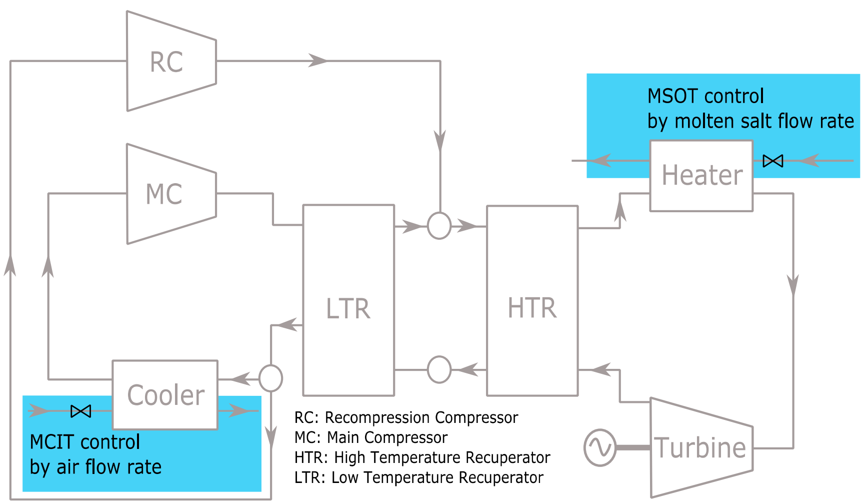
$$Nu = \frac{(f_D/8)(Re-1000)Pr}{1+12.7(f_D/8)^{1/2}(Pr^{2/3}-1)}\left(1+\left(\frac{D_h}{L}\right)^{2/3}\right)$$

$$\frac{1}{\sqrt{f_{fa}}} = 3.48 - 1.7372\ln\left(2\frac{\varepsilon}{D} - \frac{16.2426}{Re}\ln\left(\frac{(2\varepsilon/D)^{1.1098}}{6.0983} + \left(\frac{7.149}{Re}\right)^{0.8981}\right)\right)$$

Basic control loops

Controlled variable:
Molten salt outlet temperature

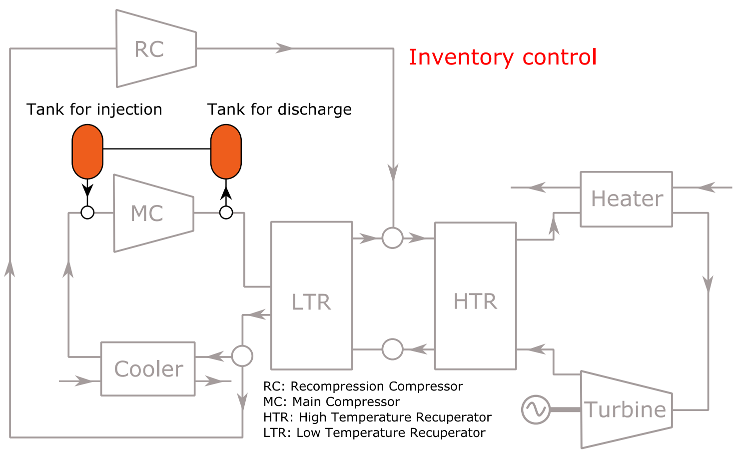
Manipulated variable:
Molten salt flow rate



Controlled variable:
Main compressor inlet temperature

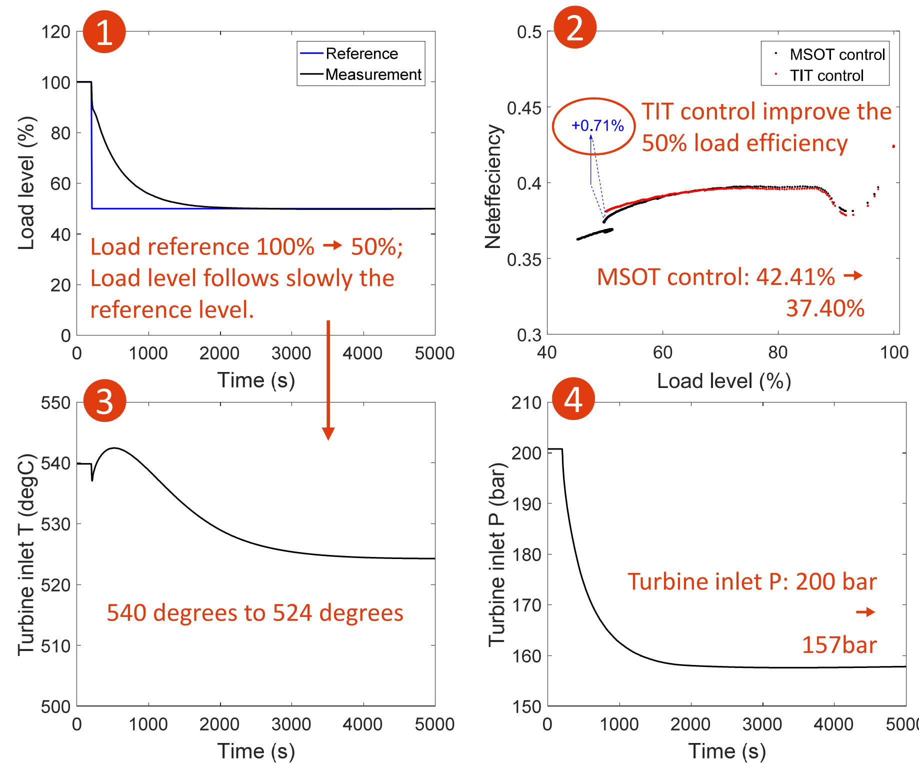
Manipulated variable:
Air flow rate

Inventory Control

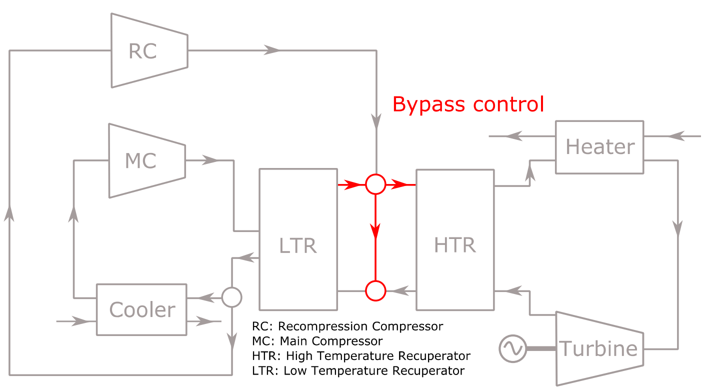


Inventory control with **Main compressor inlet pressure protection**

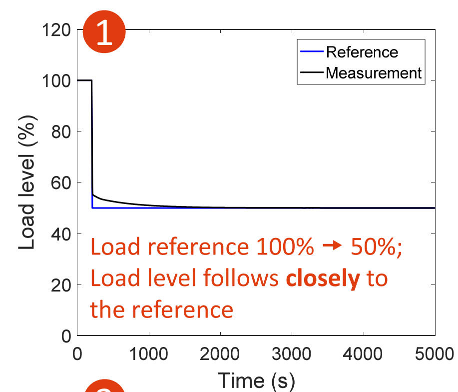
Pressure protection is important to protect compressor operation.

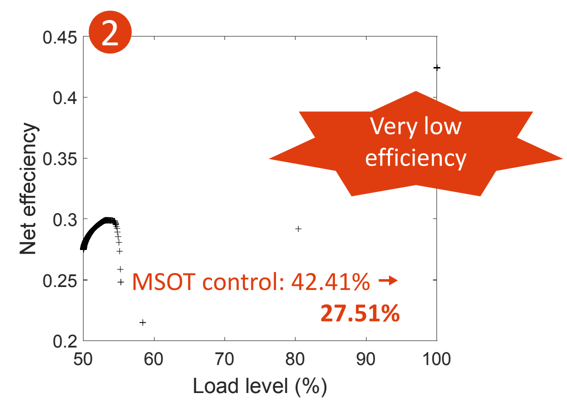


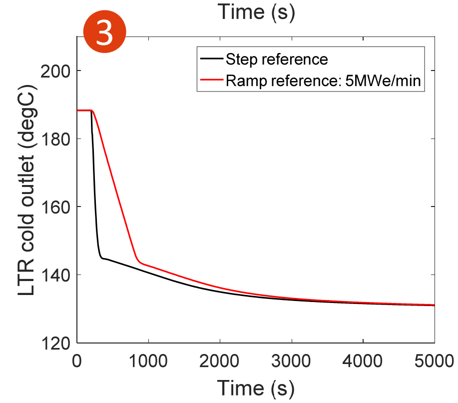
Bypass Control



Bypass control: the HTR, heater and turbine are bypassed.







Temperature near PCHEs has a high gradient.

Inventory + Bypass Control

Inventory control

High efficiency
Low response speed

With Load-inventory table:
e.g. -50% → 37.2 tons inventory discharge

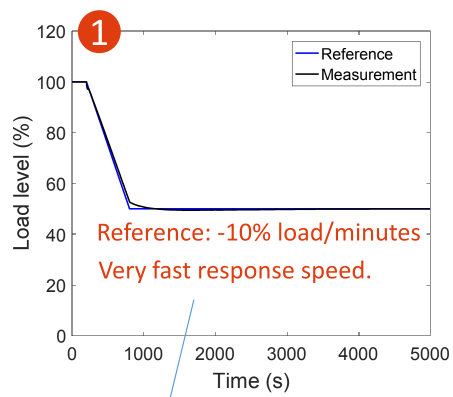
+

Bypass control

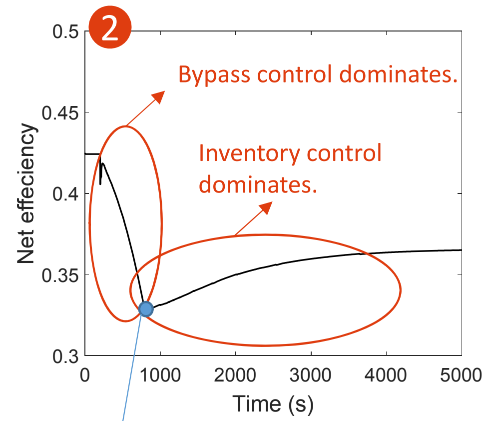
Low efficiency
High response speed

=

1. Bypass control and inventory control with load table work together at the beginning of response
2. When inventory control reaches the target amount of inventory discharging, the bypass control will stop.



Higher response time
Compared to inventory control



Min. efficiency: 32.64%
Final efficiency:36.58%

Higher efficiency
compared to bypass control

Perspectives

- A realistic dynamic model of sCO_2 recompression cycle is realized in Dymola.
- Inventory control and bypass control is a good solution for power down, but for power up, inventory control is the only choice in the current stage, whose response is not fast;

Validation and More Control Aspects

- An 20kWth experimental loop is set at the end of 2017, in collaboration with Zhejiang University, which is used to
  - Study pressure drop and heat transfer coefficients
  - Test the cycle dynamics and validate the dynamic model developed for the loop
- Mass management system will be designed to see its impact on inventory control performance;
- Investigate other part-load control strategies, in order to propose an optimized global control strategy with a good balance between efficiency and response speed for the whole range of load;
- MSOT and TIT control will be further replaced by a multi-variable control;
- Real-time optimization will be implemented to improve cycle efficiency during operation;


Merci
谢谢
Contact: Jinyi.zhang@edf.fr