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SOLAR THERMAL ENERGY
RESEARCH GROUP

# Modelling and Simulation of a Supercritical Carbon Dioxide ($sCO_2$) Concentrated Solar Power (CSP) System


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9th Renewable Energy Postgraduate Symposium

13 September 2018

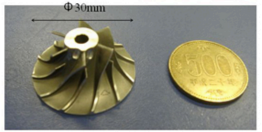

# Preface

- $sCO_2$ Brayton cycle promising alternative to steam Rankine cycle
- Can be integrated efficiently with CSP at small and large scales
- Receiving attention internationally
- Early stages of development
- Many challenges yet to be overcome

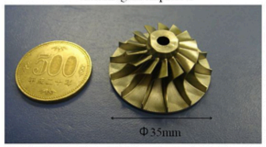
# Contents

# The $sCO_2$ Brayton Cycle

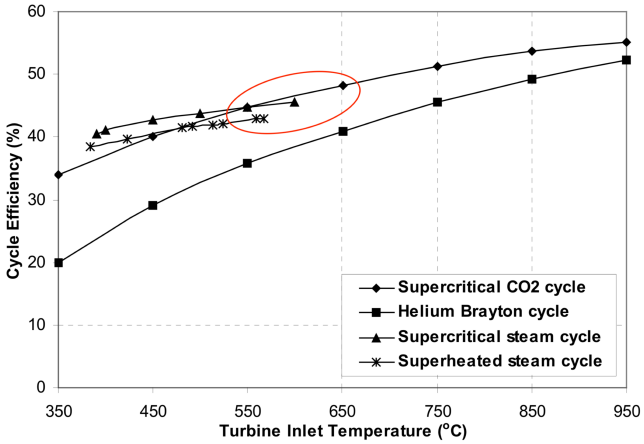
- High thermal efficiency
  - under certain temperatures and pressures
- Physically smaller equipment
  - turbomachinery and heat exchangers
- Abundant, inexpensive, non-flammable

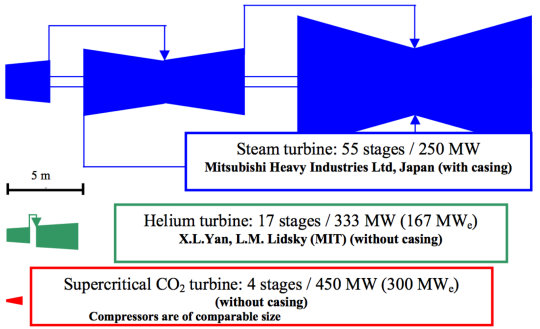


Centrifugal compressor



Radial inflow turbine

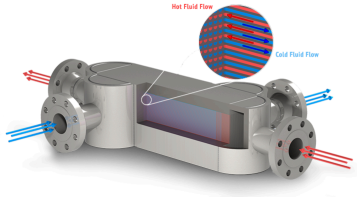


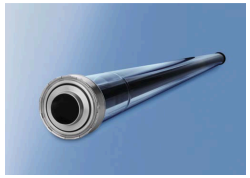



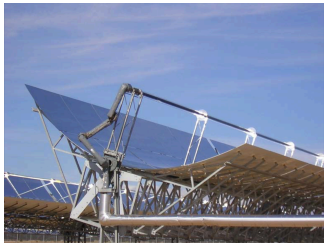

M. Utamura. *Carbon dioxide: Supercritical power.* http://www.hyoka.koho.titech.ac.jp/eprd/recently/research/448_en.html

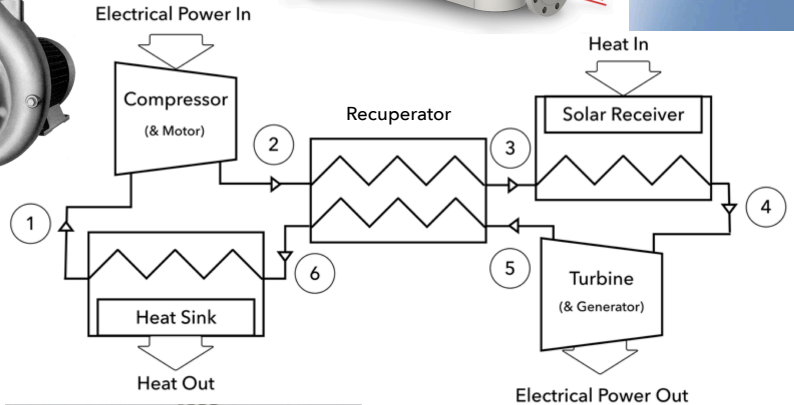
Dostal, V., Driscoll, M. & Hejzlar, P. 2004. *A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors.* Technical Report MIT-ANP-TR-100, MIT.

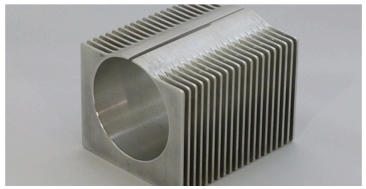
# A CSP-sCO$_2$ Brayton Cycle System

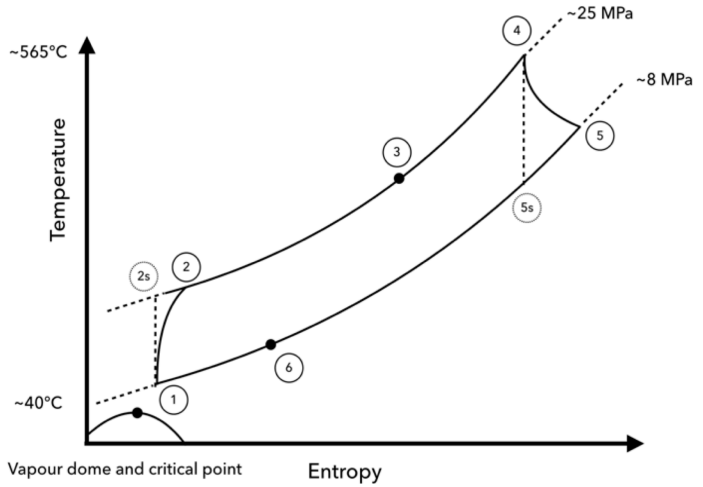


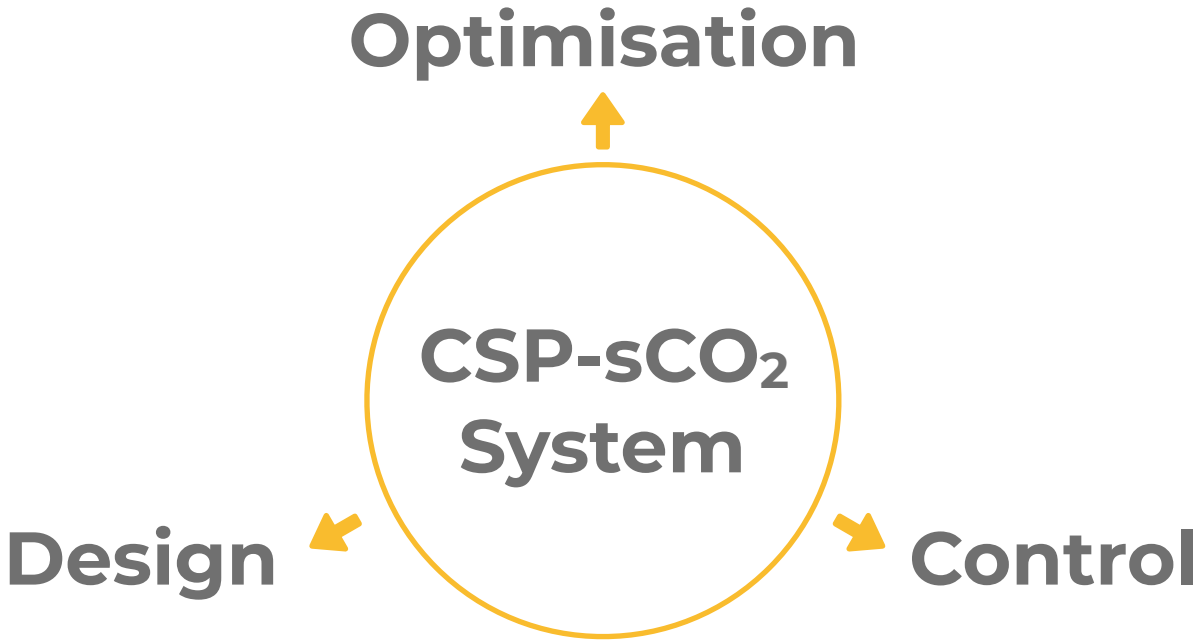






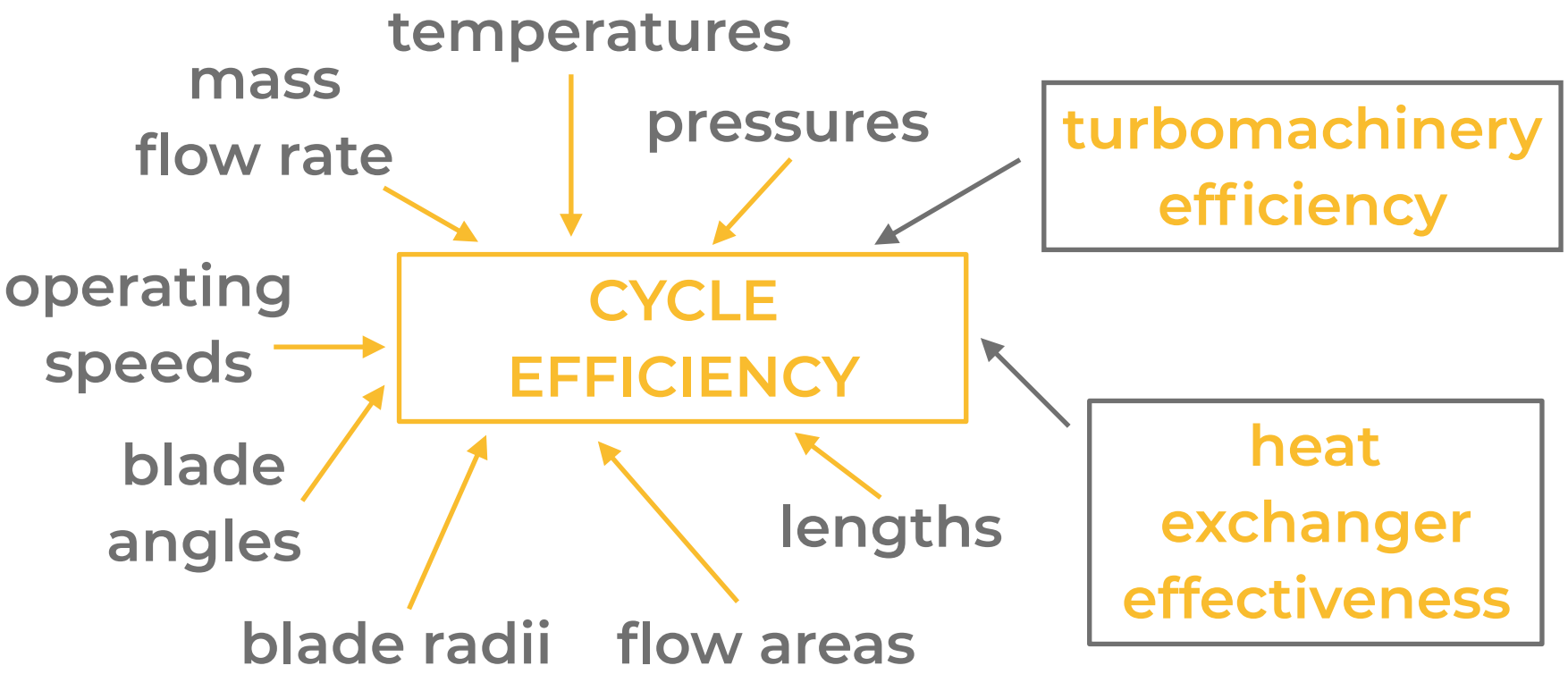
# Objectives



# Design

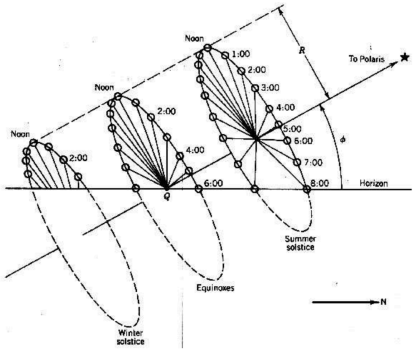
- For a known power output, determine:
  - **Cycle:**
    mass flow rate, temperatures, pressures
  - **Turbomachinery:**
    speed, blade angles, -radii
  - **Heat exchangers:**
    lengths, flow areas
- Consolidate components into cycle

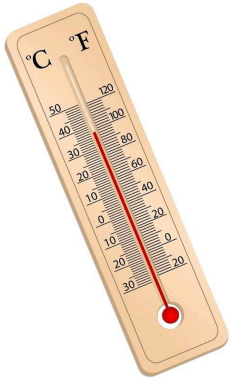
# Optimisation



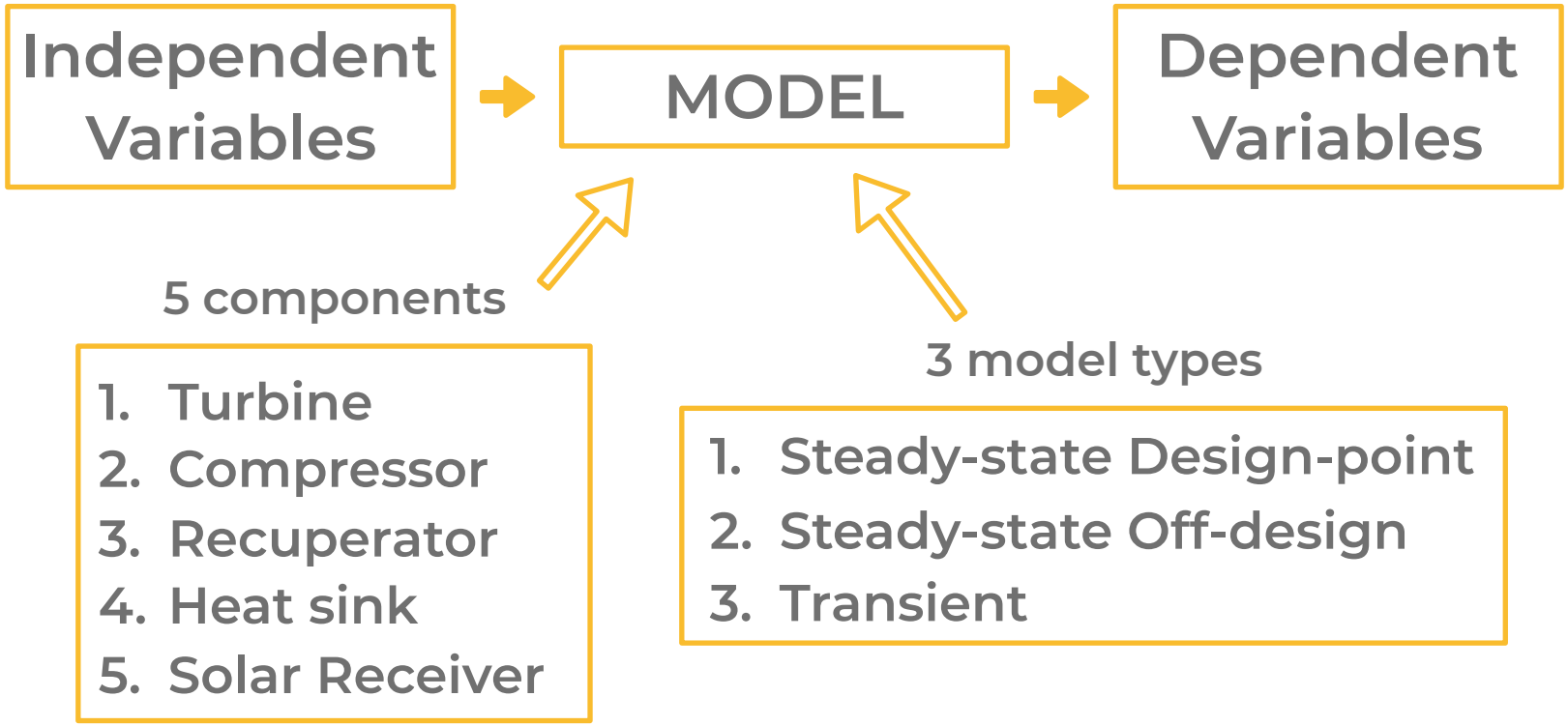
# Control

- Solar radiation level:
  - Intra-day variation
  - Seasonal variation
- Environmental variables:
  - Ambient temperature
  - Wind speed
- Operational procedures:
  - Start-up
  - Shut-down

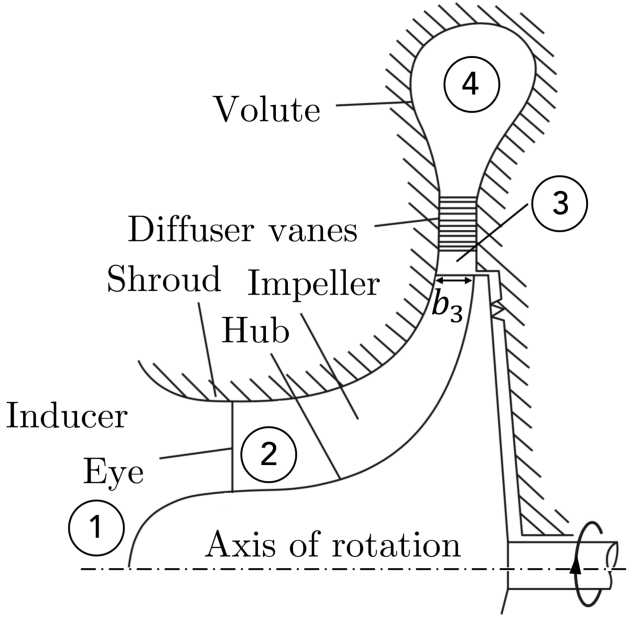


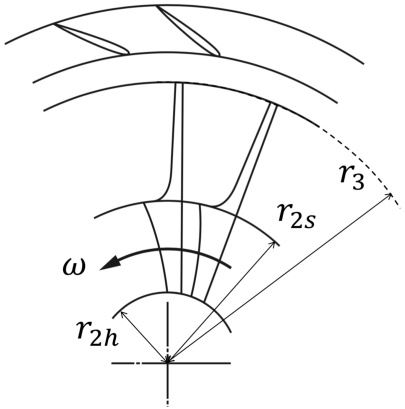



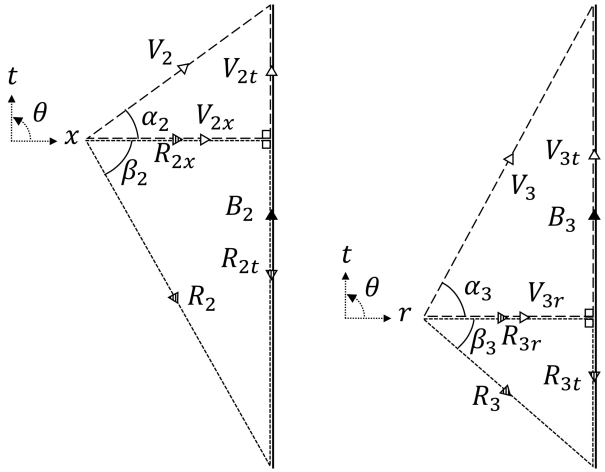

# Methodology: Principle of Modelling



# Turbomachinery Models



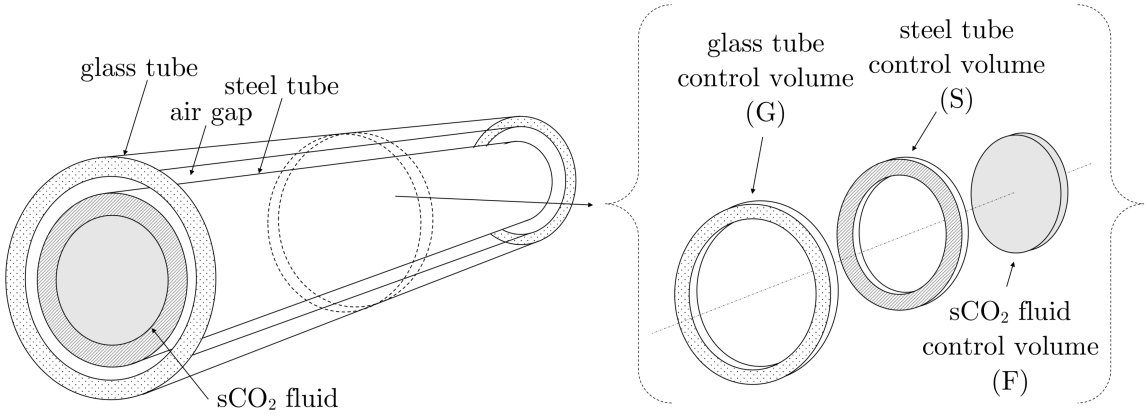



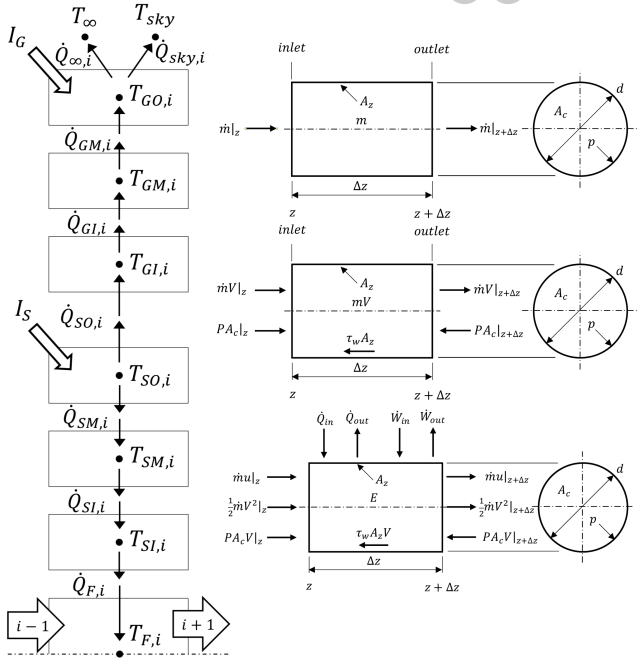

$$\dot{W}_C = \dot{m}\left(V_{3t}r_3 - V_{2t}r_2\right)\omega$$

$$\dot{W}_C = \dot{m}\left(h_{03} - h_{02}\right)$$


Dixon, S.L. and Hall, C.A. 2014. *Fluid Mechanics and Thermodynamics of Turbomachinery*. Oxford: Elsevier (7th Edition).

# Heat Exchanger Models




$L_S$

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $GO_1$ | $GO_2$ | $\cdots$ | $GO_{i-1}$ | $GO_i$ | $GO_{i+1}$ | $\cdots$ | $GO_{n-1}$ | $GO_n$ |
| $GM_1$ | $GM_2$ | $\cdots$ | $GM_{i-1}$ | $GM_i$ | $GM_{i+1}$ | $\cdots$ | $GM_{n-1}$ | $GM_n$ |
| $GI_1$ | $GI_2$ | $\cdots$ | $GI_{i-1}$ | $GI_i$ | $GI_{i+1}$ | $\cdots$ | $GI_{n-1}$ | $GI_n$ |
| $SO_1$ | $SO_2$ | $\cdots$ | $SO_{i-1}$ | $SO_i$ | $SO_{i+1}$ | $\cdots$ | $SO_{n-1}$ | $SO_n$ |
| $SM_1$ | $SM_2$ | $\cdots$ | $SM_{i-1}$ | $SM_i$ | $SM_{i+1}$ | $\cdots$ | $SM_{n-1}$ | $SM_n$ |
| $SI_1$ | $SI_2$ | $\cdots$ | $SI_{i-1}$ | $SI_i$ | $SI_{i+1}$ | $\cdots$ | $SI_{n-1}$ | $SI_n$ |
| $F_1$ | $F_2$ | $\cdots$ | $F_{i-1}$ | $F_i$ | $F_{i+1}$ | $\cdots$ | $F_{n-1}$ | $F_n$ |

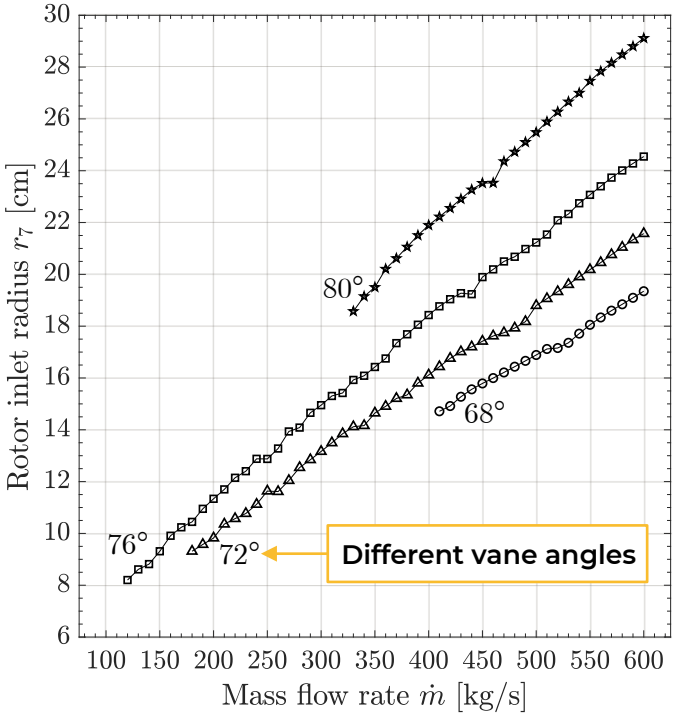
**Inlet** **Outlet**

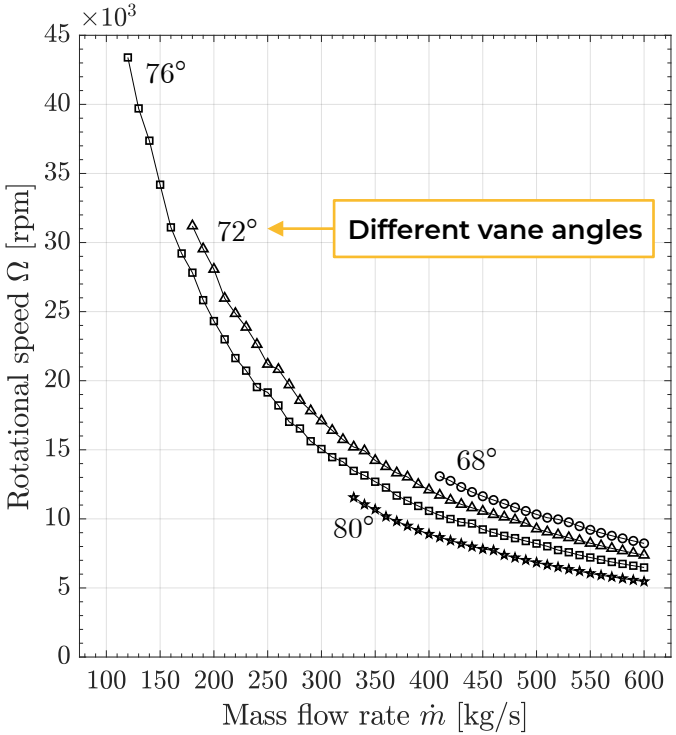
$\Delta z$

$$m|^{t+\Delta t} = m|^{t} + \int_t^{t+\Delta t} \left(\dot{m}|_z - \dot{m}|_{z+\Delta z}\right) \mathrm{d}t$$

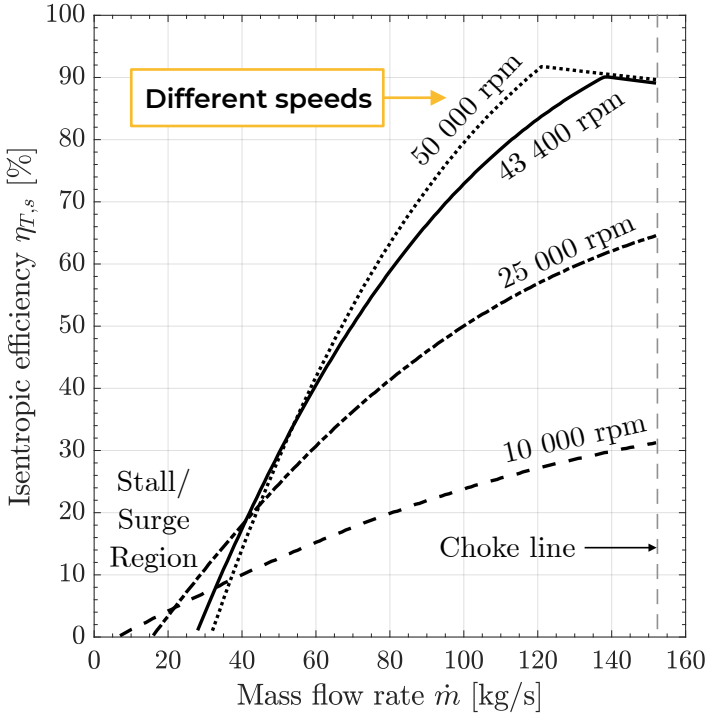
Bird, R.B., Stewart, W.E. and Lightfoot, E.N. 2002. *Transport Phenomena*. New York: Wiley (2nd Edition).

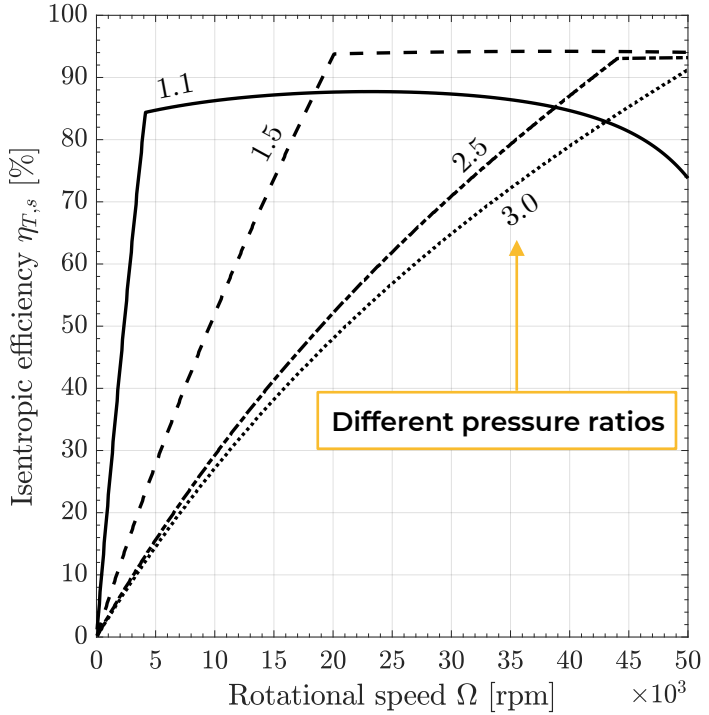
# Results: Turbine Optimisation



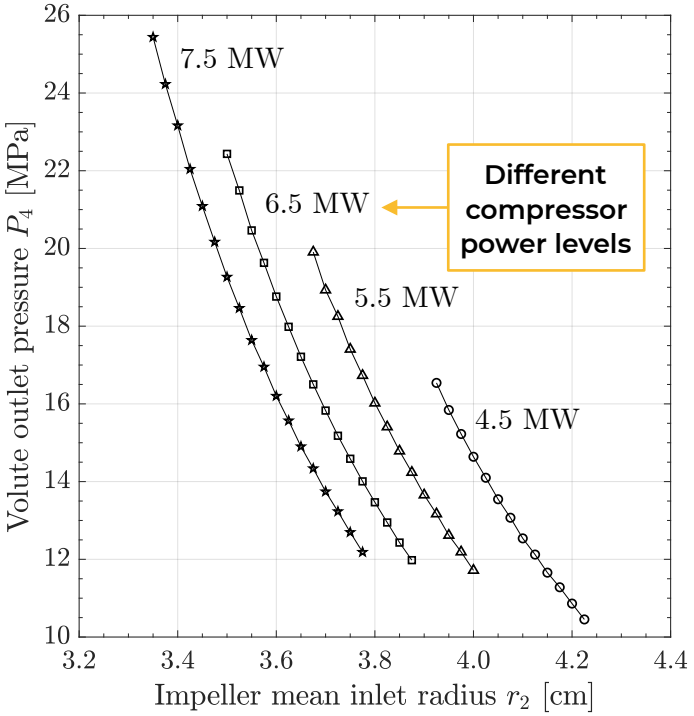



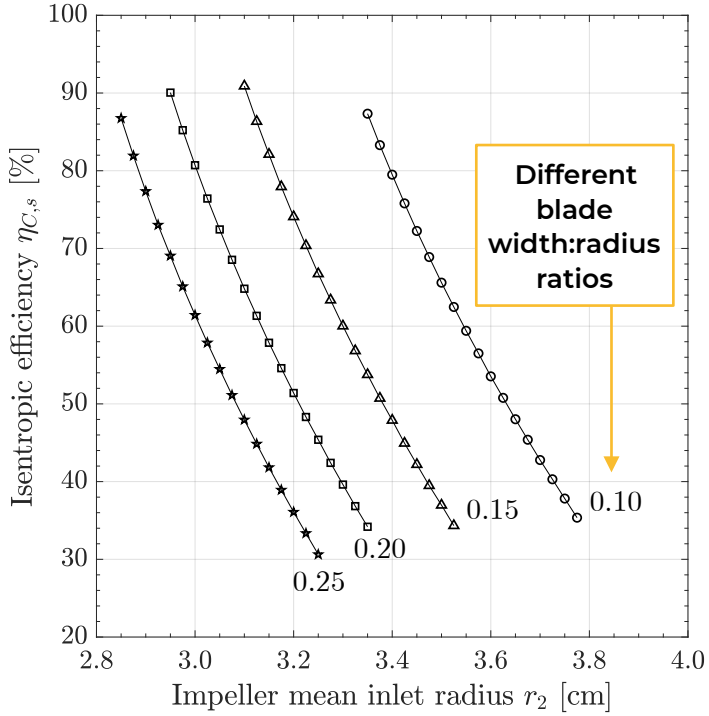
# Results: Turbine Performance Maps



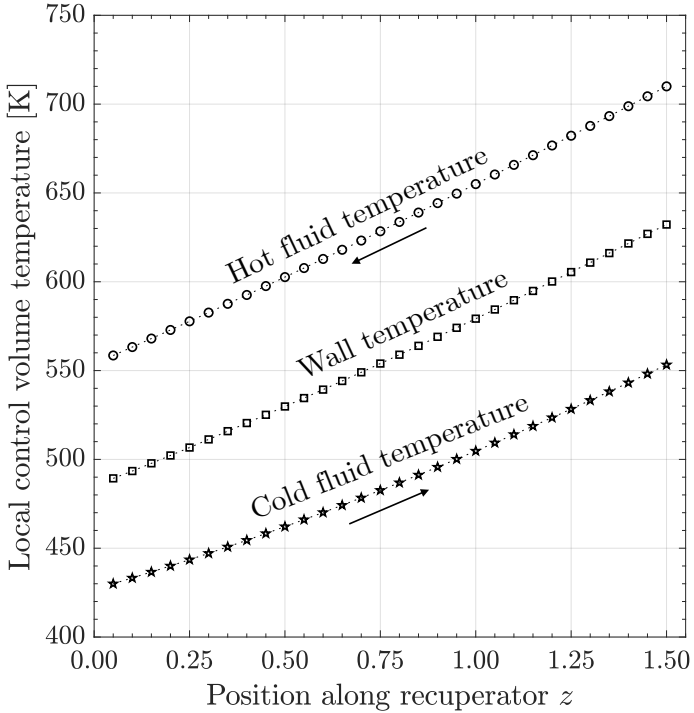



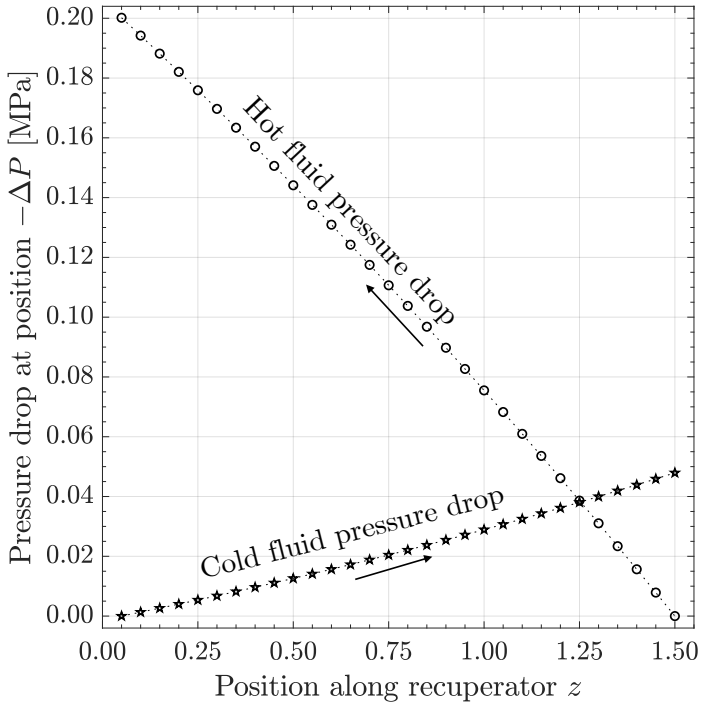
# Results: Compressor Optimisation



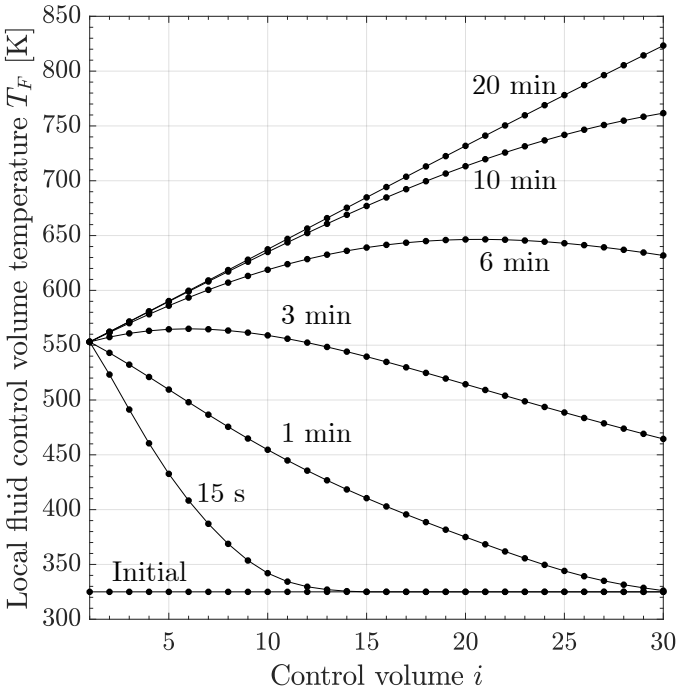



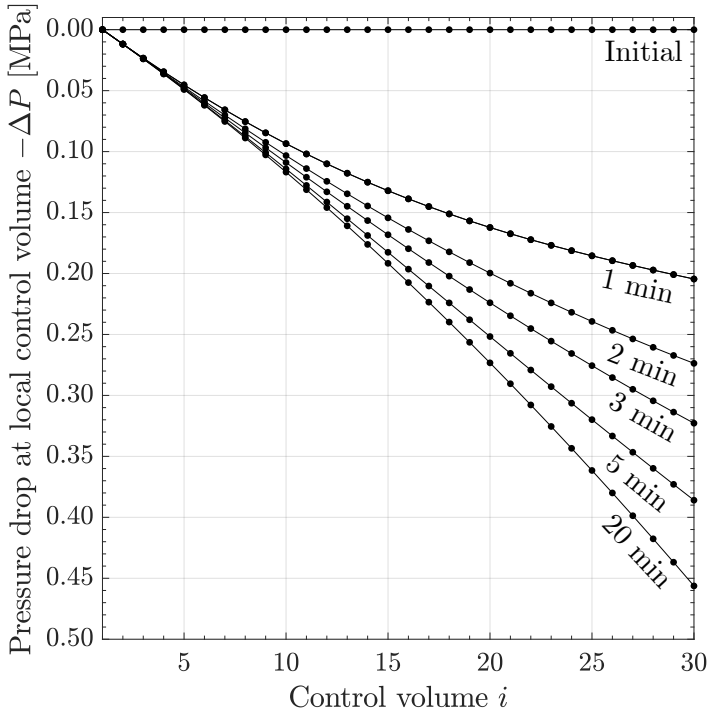
# Results: Recuperator



# Results: Solar Receiver Simulation



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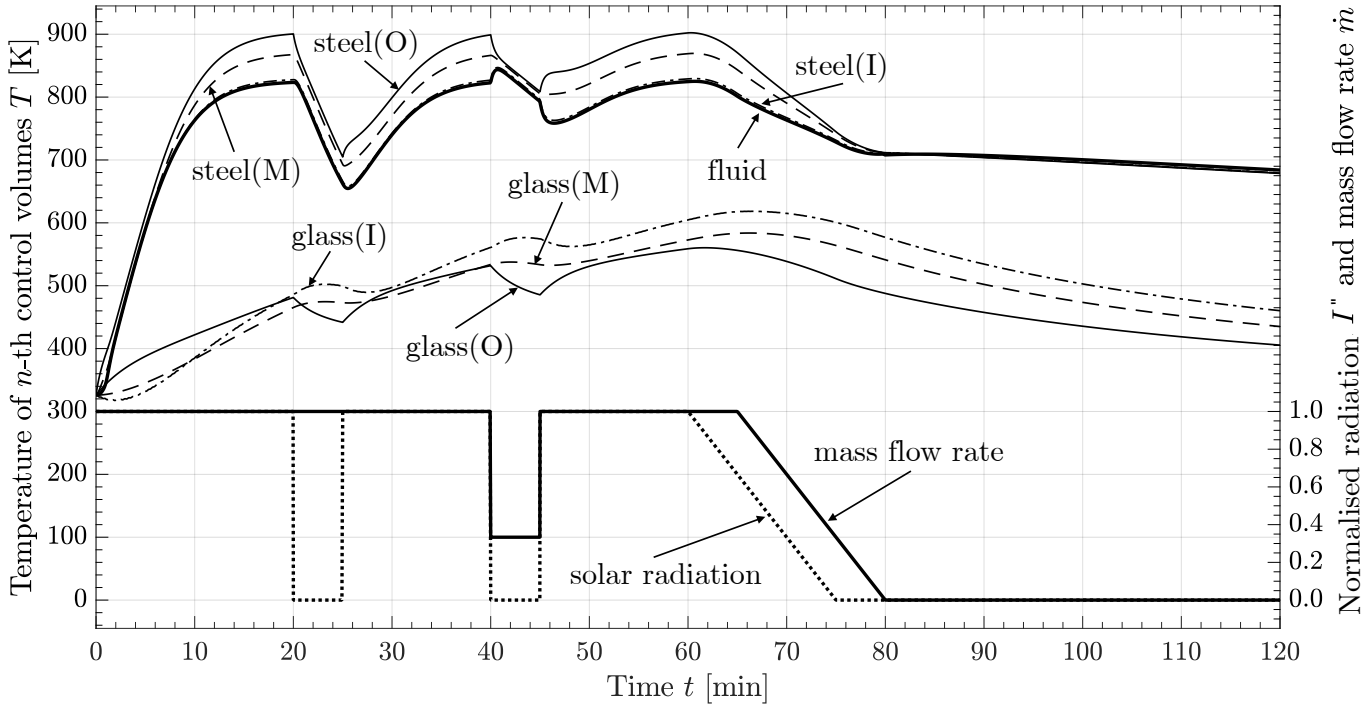

# Review and Conclusion

- $sCO_2$ Brayton cycle
  - promising new technology
  - can be integrated with CSP
- Objectives
  - integrated approach to the design, optimisation and control of CSP-$sCO_2$ systems
- Methodology
  - Modelling of cycle components
  - Different types of models
  - Velocity triangles and control volumes

## ACKNOWLEDGEMENTS:

Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University

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