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SIMULATION OF SOLAR GAS TURBINE PERFORMANCE UNDER OFF-DESIGN CONDITIONS

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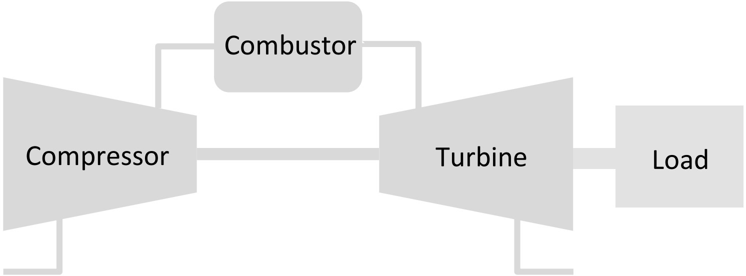
1. Background

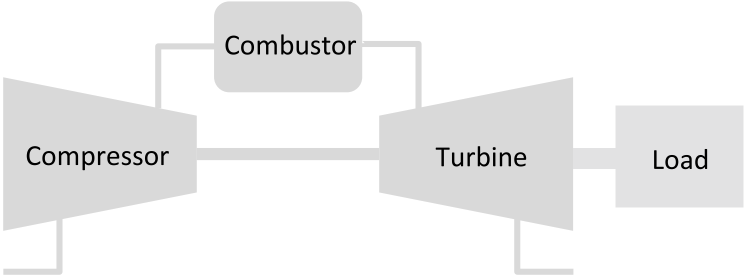
Anatomy of a gas turbine



- Compressed air is heated up in the combustor
- Expanding air rotates the turbine
- Resulting power is split between the compressor and the load

1. Background

Conditions for steady-state gas turbine operation

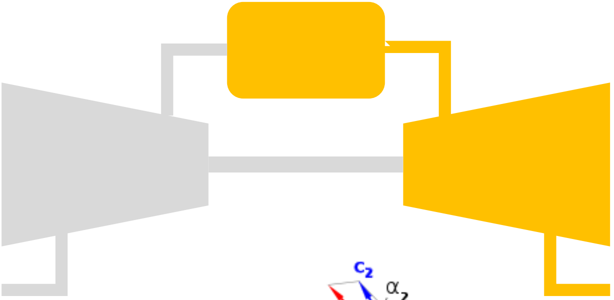


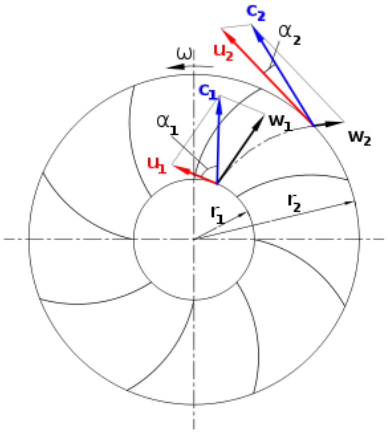
1. $\dot{m}_{comp} = \dot{m}_{turb}$
2. $r_{comp} = r_{turb}$
3. $\tau_{net,shaft} = 0$

$$N_{comp} = N_{turb}$$

2. Motivation

Off-design inefficiency in gas turbines (GTs)



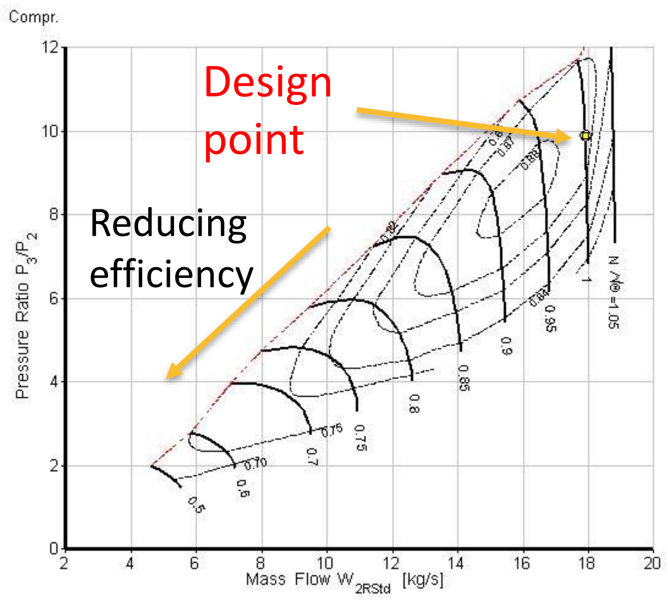


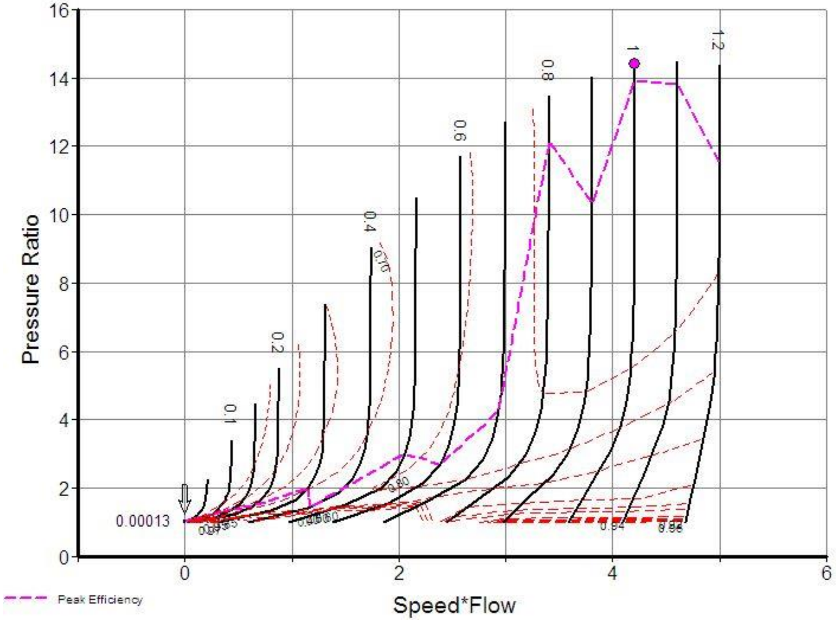
Volume flow rate proportion optimal at the design point, but differs elsewhere

Energy transfer depends on relative velocity and angle of the fluid and rotor blades

2. Motivation

Off-design inefficiency in GTs (cont.)





2. Motivation

Off-design inefficiency in GTs (cont.)

Off-design efficiency not the primary priority in common applications

- e.g. GTs for propulsion (multi-engine aircraft) spend much of their time in service near the design point
- Low weight and reliability of greater importance

2. Motivation

Attempting to improve GT off-design efficiency

Electric superchargers and electrically assisted turbochargers

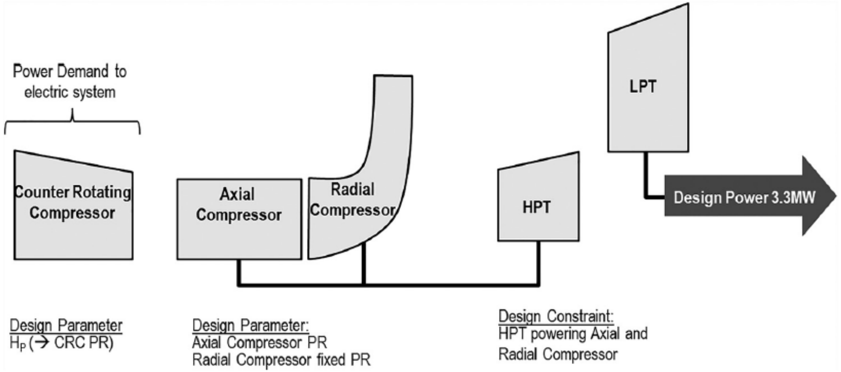
- Electric motor brings compressor rotor up to speed
- Boost pressure is attained sooner (turbo-lag reduced)

2. Motivation

Attempting to improve GT off-design efficiency (cont.)

Cycle integrated parallel-hybrid turboshaft (Vratny *et al.*, 2017)

- Turbine drives attached compressors during part load (i.e. cruise conditions)
- Motor driven auxiliary compressor enables for full load (e.g. take-off)



2. Motivation

The case for improving solar gas turbines (SGT) off-design efficiency

- Significant variations in solar irradiance
- Environmental incentive for high solar share
- Heat transfer characteristics of air are mediocre at best

3. Proposal

Research question

How may a solar gas turbine system be modified to maintain optimal matching of the energy- and volume flow rates through the system components across a wider range of solar irradiance?

3. Proposal

Objectives

- Develop a model to help assess the response of conventional- and modified SGT systems to changes in solar irradiance
- Identify and compare potential modification strategies based on practicality, performance and cost potentials
- Develop the leading strategy into a design that can be implemented to improve the off-design performance of an SGT system

3. Proposal

Current task

- Simulate off-design operation of standard GT topology, as well as the alternative
- Requires comprehensive system model

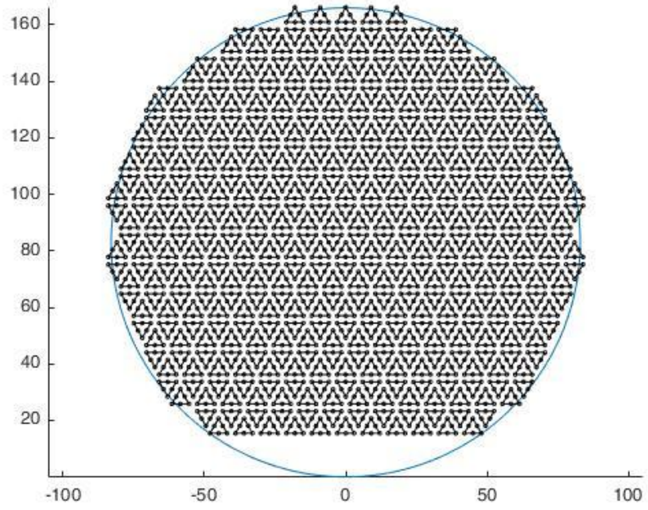
4. Modelling

4.1. Simulating thermal energy input

Ray tracing (Tonatiuh)

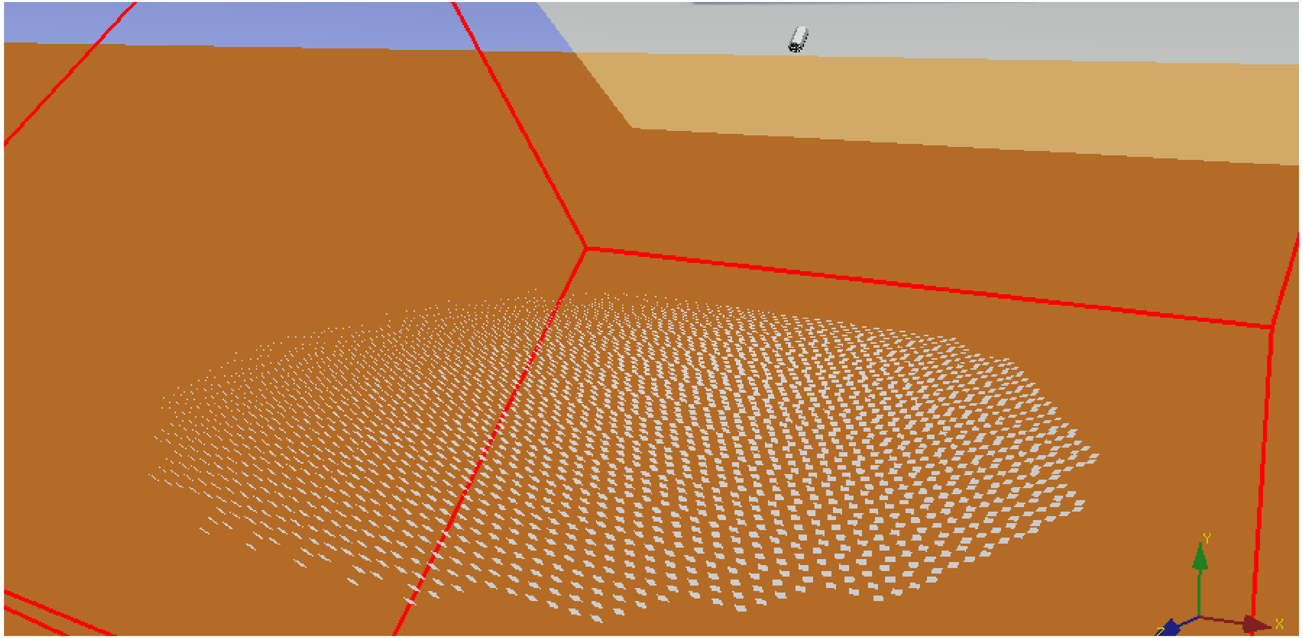
- Circular field of small-facet heliostats (HelioPods)

- Field radius adjusted until design power (5 MW) is obtained at solar noon, spring equinox (Lubkoll *et al.*, 2018)



4. Modelling

4.1. Simulating thermal energy input (cont.)

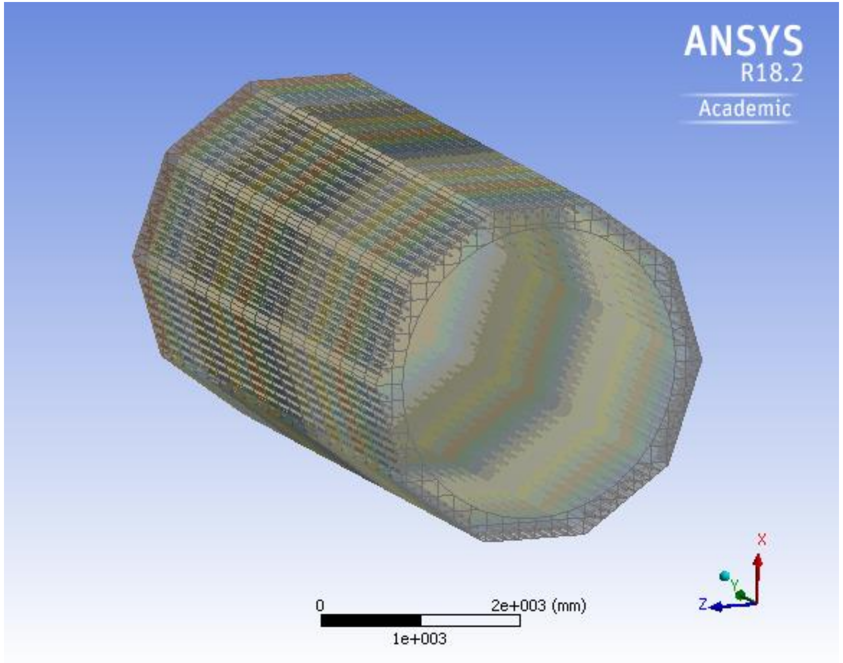


4. Modelling

4.1. Simulating thermal energy input (cont.)

Solar receiver heat transfer model

- Tubular air receiver (cavity)
- Modelled after Abengoa Solar's SOLUGAS receiver, considered state-of-the-art
- FVM model:
  - Conduction and convection terms,
  - Radiation and incident flux regarded as point sources



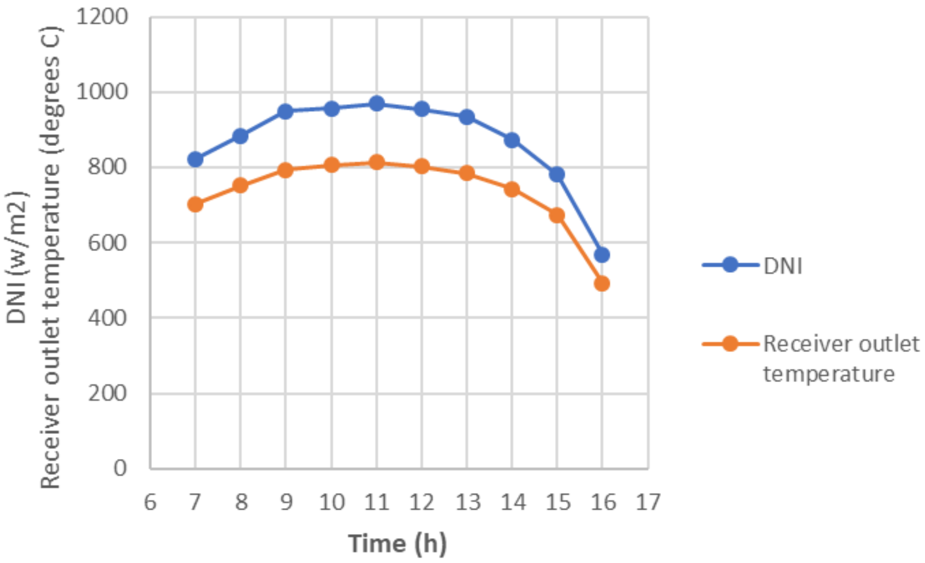
4. Modelling

4.1. Simulating thermal energy input (cont.)

Simulated Receiver performance

Change in receiver outlet temperature with irradiance as expected;

good agreement with the literature (Quero *et al.*, 2013)

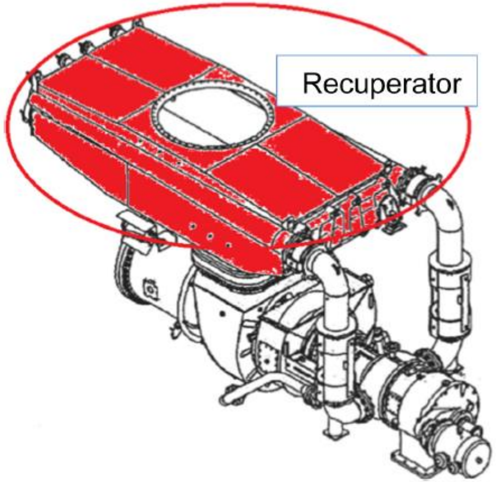


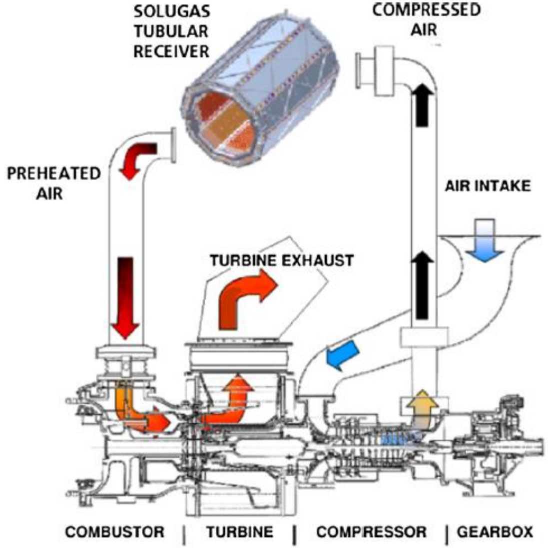
4. Modelling

4.2. Turbomachinery models

Caterpillar Mercury 50

- 4.6 MWe
- Successfully solarised in SOLUGAS project
- High thermal efficiency, recuperator readily replaceable



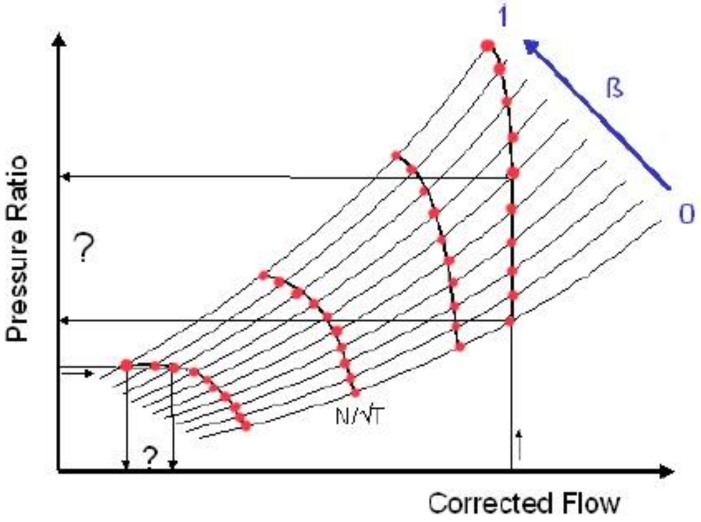


4. Modelling

4.2. Turbomachinery models (cont.)

Component characteristics:

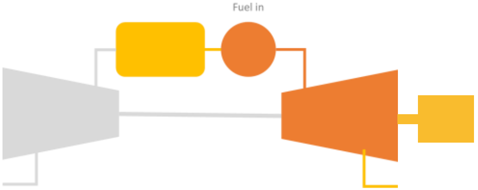
- Characteristic maps are proprietary and not easily obtained
- Analytical characteristics found to be increasingly inaccurate further away from the design-point
- Opted to scale publicly-available maps (for similar components) using GasTurb



4. Modelling

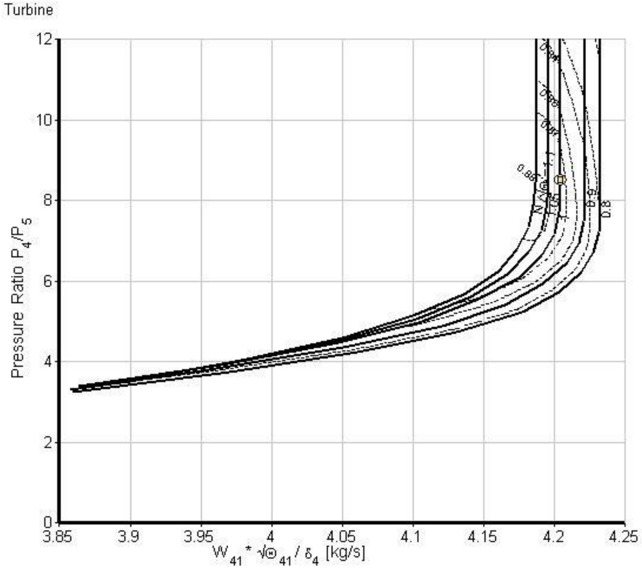
4.3. (Integrated) single shaft SGT model

Standard topology



Solution algorithm:

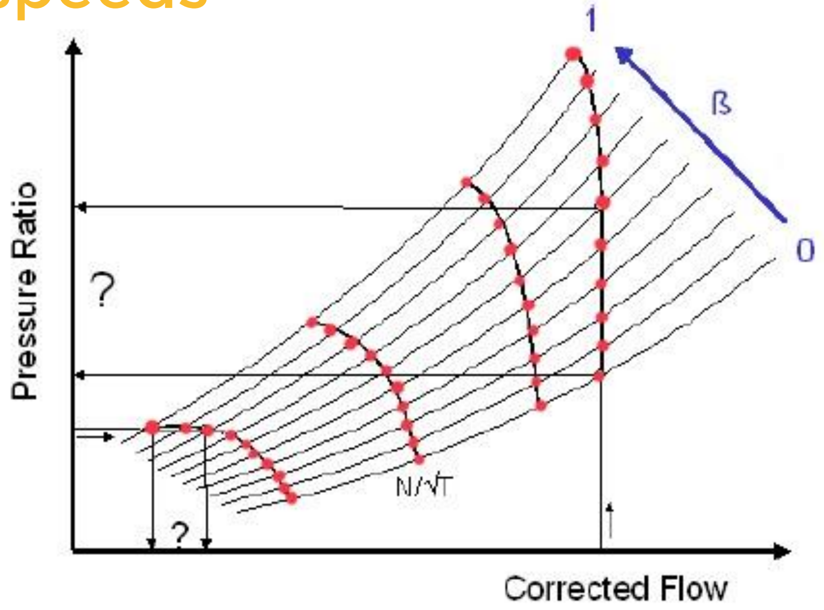
- Synchronous generator
  - one shaft speed on component characteristics
  - beta-points form a line on compressor characteristic
- Calculate temperatures and pressures sequentially
- Minimise flow error: $\dot{m}_{corr,turb\ map} - \dot{m}_{corr,turb\ calc}$



4. Modelling

4.4. Alternative topologies: independent compressor and turbine speeds

- Compressor speed not constrained
- In practice, this would require a transmission device
- Beta points now form a grid
- Calculation repeated for each point to find a solution



5. Preliminary findings

Compressor work can be reduced using a deconstructed topology

Note: figures for arbitrary electrical power output requirement (2.6 MWe)

Psolar (MW)	P_fossil (MW)	P_thermal (MW)	R_comp
0	9.23	**9.23**	9.620
2	7.19	**9.19**	9.602
4	5.18	**9.18**	9.585
9	0	**9**	9.538

Fully constrained compressor

Psolar (MW)	P_fossil (MW)	P_thermal (MW)	R_comp
0	9.13	**9.13**	7.437
2	7.05	**9.05**	7.414
4	5.05	**9.05**	7.399
9	0	**9**	7.3939

Without speed constraint

6. Future work

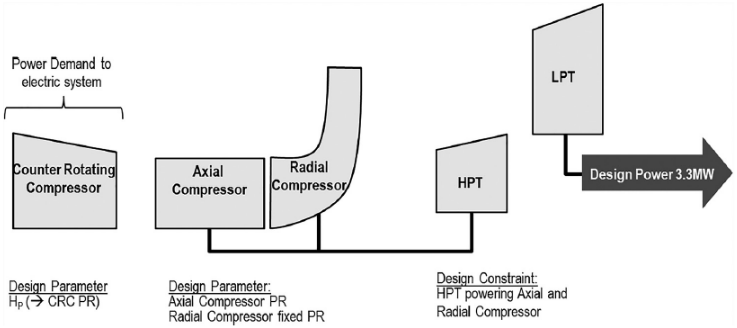
Additional modelling

- Results above are for prescribed electrical power output
- Next step: calculate the optimal power output (i.e. fuel input) for a given solar energy input
- This will multiply the number of receiver model iterations
- Simulation currently being ported from MATLAB to C++ to gain a speed advantage

6. Future work

Additional modelling (cont.)

- Incorporate pressure-loss correlations
- Simulate other topologies (e.g. auxiliary compressor) and compare results for different topologies
- Simulate transient operation (i.e. irradiance changes on the 1m, and then 1s time-scale)



6. Future work

Topology selection and design development

- Evaluate the compressor and turbine speed and torque values
- Select a suitable transmission device
  - Mechanical drive (gearbox)
  - Electrical drive (motor & generator)
  - Magnetic gearbox
- Design and construct the drive and install on Rover micro-turbine or off-the-shelf electrically assisted turbocharger

7. Concluding remarks

- Hypothesis: off-design performance of solar gas turbine can be improved by modifying the engine topology
- Preliminary findings for fully constrained and support the hypothesis
- Next steps: refine the model and select the most suitable modification device for further development
- Construct and test the modified GT topology to validate the model and assess the practical feasibility of the design

Thank you for your attention

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