Systematic Exploration of Thermodynamic Cycles for Concentrated Solar Thermal Power Generation

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Concentrated Solar Power (CSP) is a key source of renewable energy. Across a vast area of land, mirrors are strategically positioned to focus solar radiation to a specialised receiver, that heats a working fluid for the power block to generate electricity. In designing the power block, the efficiency of each component is to be evaluated and optimised, with respect to all operating conditions. By optimising the cycle through a multidisciplinary approach, the economics of CSP can become competitive with traditional energy sources.

Background

The selection and optimisation of thermodynamic cycles is fundamental to power generation. Commercially, energy is generated with the principal KPI being a high return on investment. Optimising the efficiency of energy production entails selecting a cycle design and fluid that suits the operational requirements and off-design conditions. The systems that can be feasibly implemented are based upon the Brayton and Rankine cycles, which are the focus of this research study.

Cycle Selection for CSP Conditions

In the assessment of various base cycles, different working fluids were simulated to compare capital costs, system efficiency and off-design performance, under certain CSP conditions. The power blocks analysed were the regenerative Rankine cycle, the regenerative Brayton cycle, and the hybridised Rankine-Brayton cycle. As illustrated in Figure 1, the cycles were simulated with a common temperature of 600K and a pressure ratio of 4. The experimental results indicated that the regenerative Rankine cycle exhibited the highest efficiency (Table 1). Nevertheless, since the Brayton cycle is less affected by the pressure ratio, it may have a performance advantage.

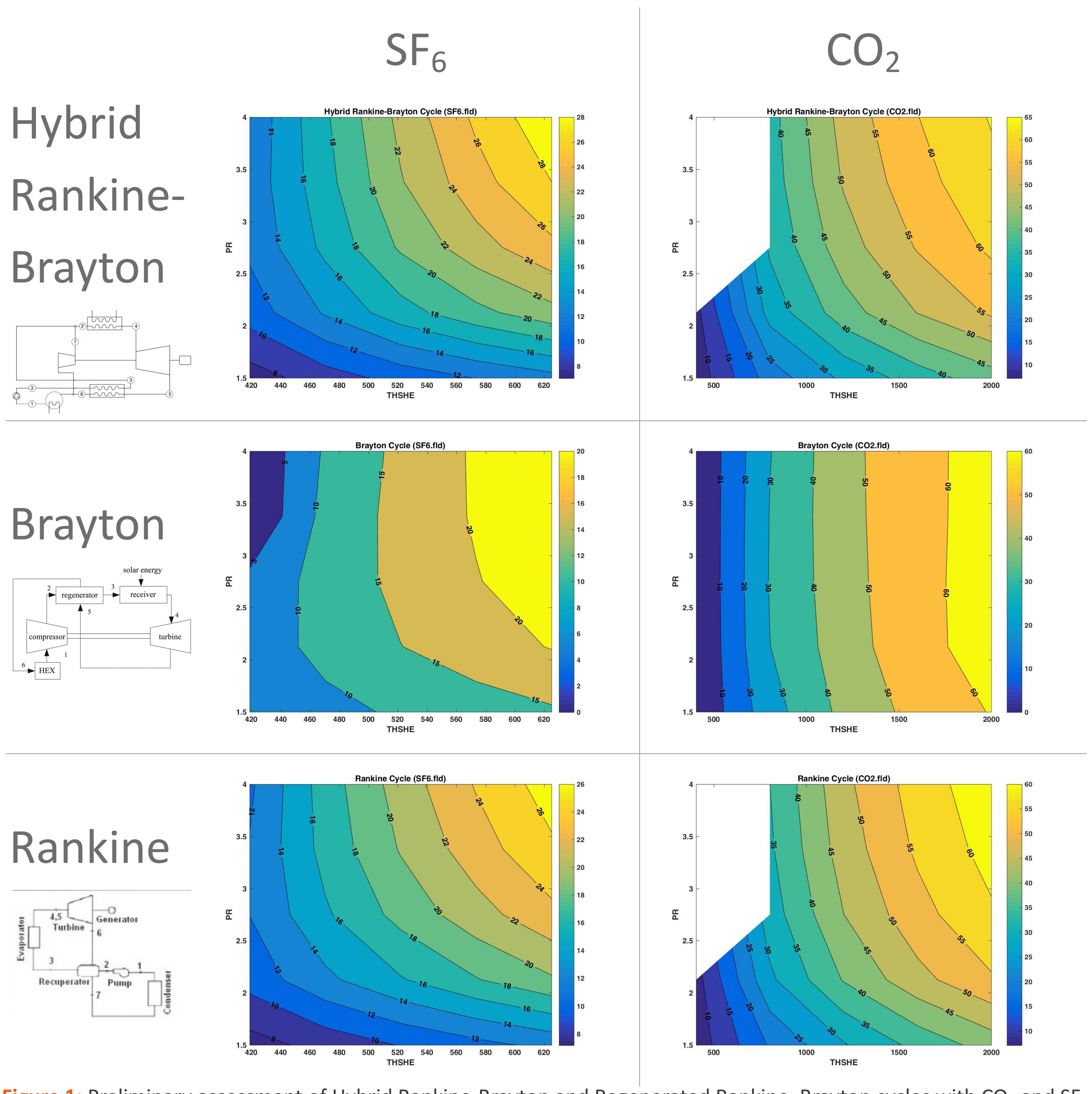


Figure 1: Preliminary assessment of Hybrid Rankine-Brayton and Regenerated Rankine, Brayton cycles with CO_2 and SF_6 as the working fluid. Contours of system efficiency for different high side temperature and pressure ratios.

Table 1: Simulation Results for Power Blocks at 600K, PR=4

	Rankine		Brayton		Hybrid Rankine-Brayton	
Fluid	CO_2	SF_6	CO_2	SF_6	CO_2	SF_6
$\eta_{thermal}$	23.32	25.66	13.27	22.57	24.50	27.98
UA	5168	6380	2620	7135	5325	11588
ε_{IHE}	0.90	0.95	0.78	0.94	0.90	0.95
$-W/kg	0.20	0.25	0.45	0.35	0.19	0.24

Multidisciplinary Design of CSP

There is a compromise between the design of the power block and solar receiver. To improve efficiency, the power block must operate at higher temperatures. However, the performance of the solar receiver is affected since more heat is dissipated via convection, conduction and radiation. Accordingly, it is important to assess both internal and external performance indicators in the development of a power block. A methodology for the systematic optimisation of design conditions is depicted by Figure 2. The graphs depict the optimal regions of operation for the regenerative Rankine cycle utilising RC318. In a 5 step procedure, the performance of standard power blocks is enhanced as specific operating conditions are determined (refer to Figure 3).

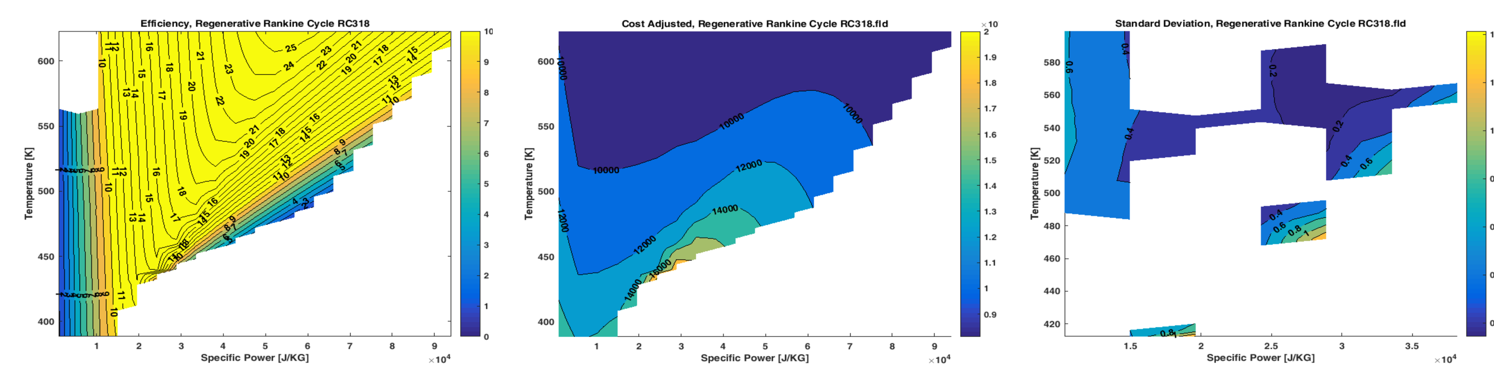


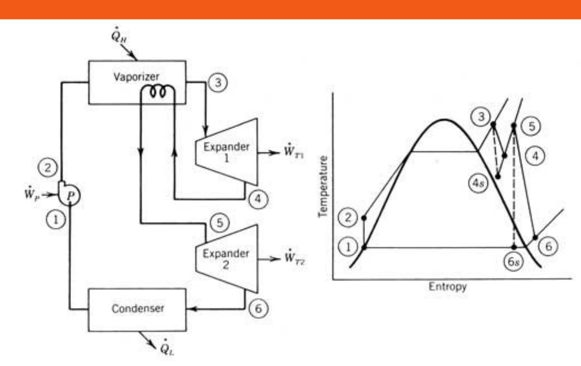
Figure 2: Evolution of optimal design from unconstrained, through cost analysis off-design performance constraints

Step 1. Assess Power Block design
Step 2. Compute efficiency of Solar Receiver
Step 3. Perform Economic assessment
Step 4. Evaluate Off-Design conditions
Step 5. Optimise Off-Design conditions

Perspectives and Future Work

In the development of a new power block from first principals, key design decisions regarding multi-stage expansion and heat reclaim processes must be made. Furthermore, the advantages of adding complexity to the system must be assessed from an engineering and economic standpoint. The inclusion of additional heat exchanges is favourable to the design point conditions. Nonetheless, the increase in capital costs and electricity expenses may not be justifiable, due to the sensitivity of the heat exchanges in off-design conditions. The performance of each cycle component, including turbines and compressors/ pumps, must be encompassed in the evaluation of the power block.

Cycle Design



Solar Receiver Performance

$$\eta_{solar} = \alpha_{rec} - \frac{\varepsilon_{rec}\sigma T_{rec}^4 - h_{conv}(T_{rec} - T_{amb})}{\eta_{field} C I_{DNI}}$$

Economic Assessment

$$\Xi_{compressor} = \frac{C_1 \dot{m}_g}{(C_2 - \eta_{pol,c}) log(\beta_2)} \sqrt{R_g/R_{ref}}$$

$$\Xi_{turbine} = \frac{t_1 \dot{m}_g log(\beta_t)}{t_2 - \eta_{pol,t}} \sqrt{R_g/R_{ref}}$$

$$\Xi_{regenerator} = 1.5 \left(r_1 \dot{m}_g P_{in,cs}^{-0.5} \Delta P^{-0.5}\right) \frac{\varepsilon}{1-\varepsilon} f$$

$$\Xi_{generator} = g_1 P_{out}^{g_2}$$

$$\Xi_{total} = \Xi_{comp} + \Xi_{turb} + \Xi_{regen} + \Xi_{gen}$$

Off-Design Analysis

$$\eta_{off} = \eta_{des} \sin\left(0.5\pi \left[\frac{\dot{m}_{off}\rho_{des}}{\dot{m}_{des}\rho_{off}}\right]^{0.1}\right)$$

minimise $\sqrt{1/\eta_{of,adj}^2 + \Xi_{of,adj}^2}$

where

$$\eta_{of,adj} = \frac{\eta_{system} - min(\eta_{system})}{max(\eta_{system}) - min(\eta_{system})}$$

$$\Xi_{of,adj} = \frac{\Xi_{adj} - min(\Xi_{adj})}{max(\Xi_{adj}) - min(\Xi_{adj})}$$

Off-Design Optimisation

minimise $\sqrt{stdev(\eta_{system})^2 + \Xi_{adj}^2}$

subject to

$\dot{m}_{des}\rho_{off}/\dot{m}_{off}\rho_{des} < 1.2$
$T_{min} < T_{des} - 20$
$T_{max} > T_{des} + 20$
$H_{min} < 0.7 H_{des}$
$H_{max} > 1.1 H_{des}$

Figure 3: Multidisciplinary approach to system design

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ACKNOWLEDGEMENTS
The Australian Solar Thermal Research Initiative (ASTRI) program is supported by the Australian Government, through the Australian Renewable Energy Agency (ARENA).

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