

## PERFORMANCE ANALYSIS OF HYBRID SYSTEMS BASED ON EXTERNALLY HEATED CLOSED-CYCLE ENGINES

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### ABSTRACT

This work presents a comparative analysis of hybrid systems that make use of closed-cycle externally heated bottoming systems. Two options are considered: reciprocating (Stirling) engines and supercritical carbon dioxide turbines. These engines share the common feature of working on closed cycles with optimised fluids ( $H_2$  and  $CO_2$  respectively). However, they differ in their internal structure: Stirling engines make use of volumetric machinery whereas the  $SCO_2$  system is composed by turbomachinery. In both cases, the working fluid is subjected to very high pressure and temperature in the range of 50-200 bar and 40-650 °C.

A brief description of both bottoming systems is provided in the article along with the expected performance of each case in on-design and off-design (part load) conditions. The analysis is therefore split into two stages. First, a comparison is shown for on-design operation aiming to evaluate the maximum efficiency attainable by the proposed systems. Second, a preliminary analysis of off-design operation is presented.

The paper concludes that hybrid systems based on atmospheric fuel cells and externally heated closed-cycle bottoming engines have the potential to outperform conventional pressurised fuel cells and gas turbines hybrids while preserving the topping system from the demanding operating conditions of the latter configuration

### INTRODUCTION

The aim of this work is to develop a new concept of hybrid system based on a topping molten carbonate fuel cell and a bottoming externally heated heat engine. The integration is of the indirect type (there is heat exchange but no mass transfer) what brings about a higher life expectancy of the fuel cell due to its atmospheric operation. Other interesting features from a global standpoint are ease of operation and load control and

possibility to operate the fuel cell in stand-alone mode.

The first heat engine considered is a closed-cycle gas turbine operating with supercritical carbon dioxide. This is a configuration studied extensively so far by the authors who report a better performance of such system with respect to conventional hybrid systems (with either indirect or direct integration) both in on-design and off-design conditions [1,2]. The advantage of supercritical fluids is the very low work required to elevate the fluid's pressure at the compressor and hence the higher net work of the system. The interest of carbon dioxide lies in the close to ambient critical temperature (30.98 °C) and low critical pressure (71 bar). These properties make it possible to develop supercritical cycles with conventional cooling techniques and economical piping.

The second heat engine under consideration is a Stirling engine. It is also a closed-cycle engine but makes use of a reciprocating configuration. The working fluid of a Stirling engine can be hydrogen, helium, nitrogen or simply air; in the present paper, hydrogen is selected for it yields the best performance [3].

A Stirling engine comprises: (i) a pair of cylinders where the fluid is compressed at low temperature and expanded at high temperature, (ii) a heater and a cooler to add and reject heat to and from the engine respectively, (iii) a regenerator placed in the middle of these heat exchangers in order to increase the efficiency. The main advantages of this engine are compactness, low vibrations, low noise and good part load performance. Durability and efficiency are also to be expected to these depend on the design operating conditions [4].

### DESCRIPTION OF HYBRID SYSTEMS

A general layout of the hybrid system proposed is shown in Fig. 1. A Molten Carbonate Fuel Cell is fed with preheated air and a mixture of water steam and natural gas that is indirectly reformed internally. The necessary

steam for the reforming process is generated outside of the cell in a dedicated steam generator that recuperates a fraction of the waste heat from the system. A catalytic burner is located in the cell exhaust to burn the inevitable excess fuel and increase the temperature of the heat source used to operate the bottoming engine (let it be noted that a minimum temperature of 700°C is required if the heat engine is to achieve high efficiency).

A fraction of the gas leaving the heat exchanger that transfers heat from the topping to the bottoming system (HX4 in Fig. 1) is recirculated to provide the cathode of the cell with the carbon dioxide necessary to avoid carbonate starvation. The remaining gas is used to preheat the fuel and air streams into the cell.

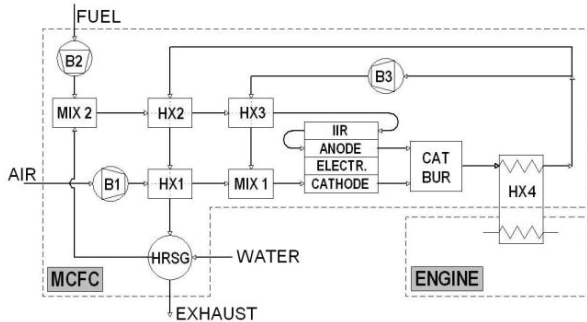


Figure 1. Hybrid system layout.

### HYBRID SYSTEM PERFORMANCE

Table 1 shows the performances of the two hybrids considered along with that of a conventional system using a hot air turbine. In all cases the cell operates at atmospheric pressure. Regarding the Stirling engine, the rated operating conditions are 150 bar mean pressure and 650 °C head temperature (wall temperature of the pipes that form the heater). The shaft speed is 1500 rpm.

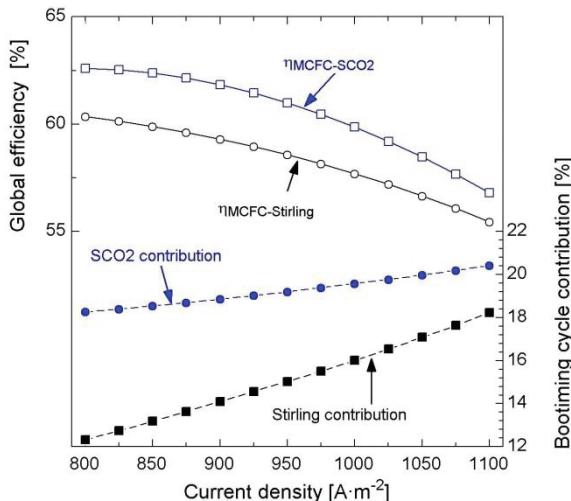


Figure 2. Part-load performance (efficiency and contribution of the bottoming cycle to total power).

The part-load performance of the systems is shown in Fig. 2 where it is assumed that both closed engines adopt

an inventory control system. For the sake of clarity, the conventional system has not been included in the figure.

At low current densities, the fuel cell exhaust mass flow rate decreases and so does the available heat for the bottoming cycle (which then operates with lower efficiency at part-load). Nevertheless, due to the higher efficiency of the cell at part-load, the global efficiency of the system is higher. In this regard, the reason why the Stirling engine experiences a steeper drop in efficiency is the lower internal pressure at part-load.

Parameter		Air	SCO <sub>2</sub>	Stirling
MCFC	Current density [ $A\ m^{-2}$ ]	1100		
	STCR [-]	3		
	Temperature [K]	923		
	Fuel/CO <sub>2</sub> utilization [%]	75/70		
	Efficiency [%]	48.94		
CYCLE	Compressor inlet [ $^{\circ}C/bar$ ]	25/1.01	35/75	650 °C
	Turbine inlet [ $^{\circ}C/bar$ ]	650/2.88	650/216.1	150 bar
	Efficiency [%]	26.6	39.9	34.5
HS	Net efficiency [%]	53.1	57	55
	Net power [kW]	521.2	553	539.8
	Heat engine fraction [%]	14.7	20.4	18.2

Table 1. Rated performance.

### CONCLUSIONS

The results shown in this work allow drawing the following conclusions:

- Hybrid systems based on a closed-cycle externally-fired heat engines achieve higher efficiencies than conventional systems under rated operating conditions. For a reference case, it is expected that the supercritical carbon dioxide turbine be close to 60% whereas the conventional system using a hot air turbine does not even reach 55%. This latter figure can be expected from the Stirling-based hybrid.
- The hybrid systems proposed exhibit an excellent part-load efficiency. At medium to high loads, the SCO<sub>2</sub> turbine seems to be the most.
- Globally, the interest of the proposed systems can be confirmed by looking at the contribution of the bottoming engines to the power produced by the system. While this fraction typically decays fast with load for conventional hybrids, it remains at high values for both the SCO<sub>2</sub> turbine and the Stirling engine.
- Finally, it is worth noting that the Stirling engine is more attractive in terms of technology readiness.

### REFERENCES

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