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POWER GENERATION FOR AFRICAN RURAL COMMUNITIES: INITIAL ASSESSMENT OF HIGH TEMPERATURE THERMAL ENERGY STORAGE FOR SMALL-SCALE SOLAR BRAYTON SYSTEM

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ABSTRACT

This paper focuses on a small-scale solar-driven system for power generation in remote, off-grid, rural areas. In particular, the research investigates a small-scale thermal Brayton system suitable for power output < 10 kW. The study addressed the need of thermal energy storage integration into the main process to extend operability and electricity generation when solar irradiance is lower than the design value or insufficient to drive the process. The work combines both experimental and numerical methods to investigate integration of TES and four different types of TES materials.

Keywords: Solar thermal, small-scale Brayton, thermal energy storage, phase-change materials.

1. INTRODUCTION

Providing affordable energy to Africa is one of the paramount challenges of the 21st century. Currently, 80% of Africans in rural and remote areas do not have access to electricity. Overall, more than 600 million people do not have access to electricity or use dangerous forms of energy [1]. Grid interconnection is not often a feasible option. It often remains technically unfeasible, inefficient and too costly. On the other hand, small-scale distributed electricity generation systems can be deployed in villages, local communities and remote areas [2]. Furthermore, small scale generation has the potential to benefit from the immense renewable energy sources (RES) available in Africa. However, finding viable energy storage solutions is the key to mitigate the intrinsic intermittency of RES and ensure energy supply.

Despite the urgency and huge potential, limited research has been performed in this area. This paper assesses the integration of thermal energy storage (TES) with a small-scale solar Brayton cycle (SSBC) suitable to produce electricity (3-10kW) for rural communities [3,4]. The work addresses the modelling of a SSBC for the design and integration of high temperature (500-700°C) TES technology capable of storing solar thermal energy and making it available when the sun is not shining, therefore enabling reliable electricity generation with the SSBC system.

Fig 1: SSBC installation at the University of Pretoria.

Figures 1 and 2 illustrate the SSBC system being developed at the University of Pretoria and investigated in this work. The SSBC captures solar radiation through the solar dish to produce hot air (600-700°C) which drives a small-scale gas turbine to generate electricity. The availability of electricity generation is clearly linked to the availability of solar irradiation. Such configuration was considered as baseline configuration for the present investigation on TES integration. Table 1 summarizes the main parameters of the system considered.

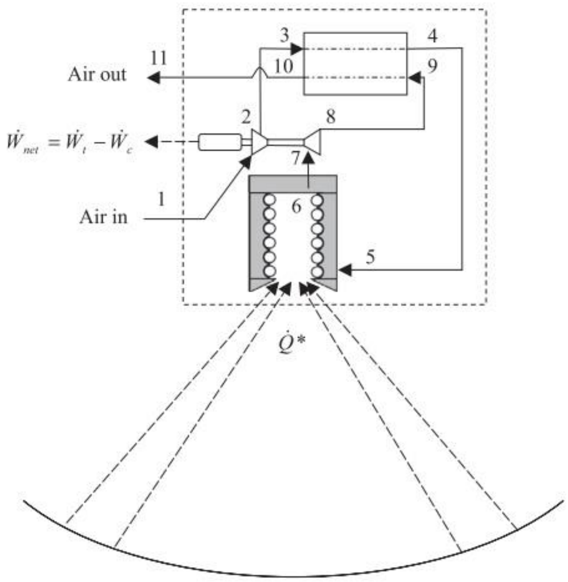

Fig 2: Process flow diagram of the SSBC system [4].

Table 1: Chosen operating parameters.

Operating Condition:	Data
Air flow rate, *G* [kg/s]	0.0593
$\beta_{,compressor}$ [-]	1.487
$\beta_{turbine}$ [-]	1.456
Receiver:	**Data**
Cavity geometry [m^2]	0.25 x 0.25
Depth Receiver h_{rec} [m]	0.5
Steel Tube Emissivity [-]	0.7
Collector:	**Data**
Diameter [m]	4.8
$\eta_{optical}$ [-]	0.95
η_{reflec} [-]	0.85
Recuperator:	**Data**
Width [m]	0.5
Length [m]	0.6
Height channel [m]	0.002
Number of channel pairs [-]	40
Thickness plate [m]	0.001

2. PROCEDURES AND METHODS

2.1 *Experimental method*

A combination of experimental and numerical methods has been adopted to identify the configuration of a SSBC system integrated with thermal energy storage (TES). Experiments were performed to capture the performance and efficiency losses of key sub-components of the SSBC system. In particular, the coiled tubular receiver was instrumented with 14 K-type thermocouples measuring the surface temperature of the receiver. Furthermore, the temperature of the ceramic fiber insulation surrounding the receiver was also instrumented in order to measure the relevant temperature so that the heat losses could be calculated.

The mass flow rate of air travelling through the receiver tube was determined with an anemometer (Kestrel 5 000 Pocket Air Flow Tracker) which was used to measure air velocity. The temperature of the fluid was recorded with instream thermocouples and corrected to account for the radiation effect. Finally, direct normal solar irradiance was measured with a Kipp & Zonen solar measuring device which is part of the SAURAN network.

2.2 *Modelling methods*

Also, a model was developed at the University of Birmingham (UoB) in order to accurately predict and characterize the thermodynamic processes taking place within the SSBC system and design an alternative SSBC configuration with an integrated TES device. The main model includes sub-component models (energy, mass, entropy balance equations). This allowed for the evaluation of the thermodynamic properties at the various positions in the cycle. Furthermore, the model was tuned in order to account for the daily variation of solar irradiance (data from Pretoria, South Africa).

3. MAIN FINDINGS

3.1 *Experimental results*

Figure 3 and Table 2 show the receiver testing results which were captured on the 20th of June, 2018. The figure depicts the time evolution of the inlet and outlet temperatures, the surface temperatures along the length of the solar receiver tube as well as the insulation outer surface temperatures. A gas burner was used to simulate a typical receiver inlet temperature so that the heat losses from the receiver could be determined. The first test (in stow position) reached steady state at about 4500 s, the second test (with solar exposure at 40^o elevation angle: DNI of 942 W/m^2) at about 9000 s and the third test (tilted at 40^o elevation angle, but without solar exposure) at about 12 000 s.

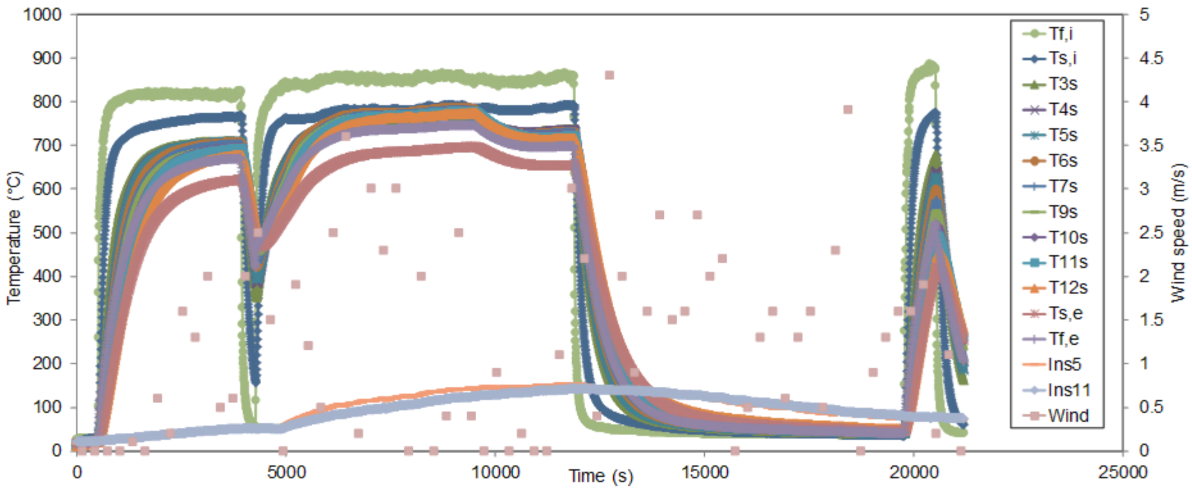

Fig 3. Experimental test of the SSBC solar receiver, including wind measurements.

Table 2: Steady-state temperatures (in degrees Celsius) for Test 1, 2 and 3 without correction for radiation effect.

Test	$T_{s,i}$	T_{3s}	T_{4s}	T_{5s}	T_{6s}	T_{7s}	T_{9s}	T_{10s}	T_{11s}	T_{12s}	$T_{s,e}$	$T_{f,i}$	$T_{f,e}$
1	769	709	706	708	706	703	698	695	691	678	622	824	671
2	790	769	772	772	786	781	783	778	777	773	696	851	747
3	787	732	731	723	727	726	722	722	719	715	654	851	697

3.2 *Numerical results – SSBC integrated with thermal energy storage*

An initial assessment was performed to quantify the excess of solar thermal energy available for the SSBC system. This was crucial to identify the feasibility and storage capacity of a TES integrated with the process. The analysis was carried out by combining the experimental measurements (solar irradiance) and the mathematical model developed. This allowed to identify charge and discharge periods. The results are shown in Figure 4. The modelling analysis indicated that the SSBC requires a minimum irradiance of 850-900 W/m^2 to operate. Therefore, surplus of solar energy was typically found from 9AM to 4PM. Hence, the stand alone SSBC cannot operate outside the 9AM-4PM time frame (lack of solar radiation), while within the time frame 9AM-4PM excess solar energy is available

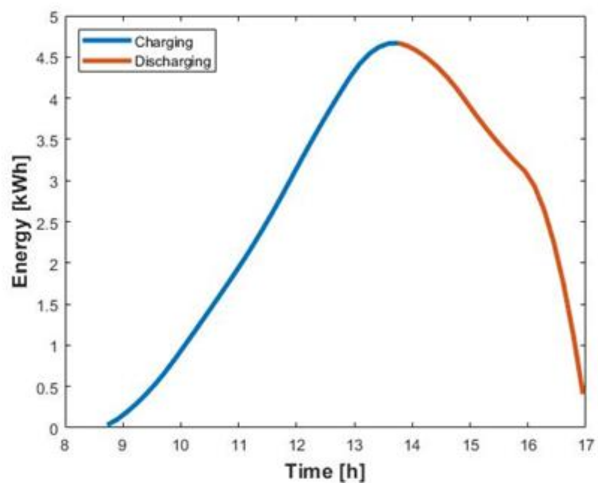

Fig 4: TES charging/discharging duty cycle.

3.3 *Proposed configuration for SSBC with TES*

The process configuration illustrated in Figure 5 was proposed. The layout allows the bidirectional flow of air through the TES system. The latter was considered to have a packed-bed type configuration to enable heat transfer between the air and the TES material.

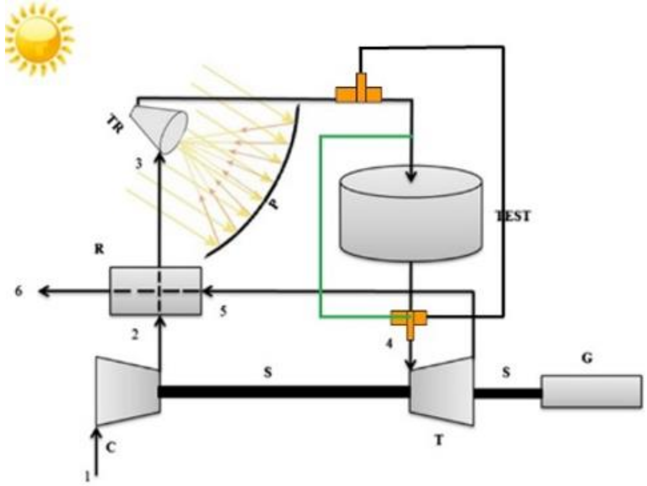

Fig 5: TES charging/discharging duty cycle.

Table 3: Techno-economic parameter of TES system

Material	ρ $[kg/m^3]$	c_p $[J/kg\ K]$	C $[USD/kg]$	T_m [°C]	L [kJ/kg]
Rock	2560	960	0.15	-	-
Concrete	2750	916	0.05	-	-
Na_2SO_4	2664		10.4	844	165
$SrCl_2$	3052		43.3	875	103

Four storage materials were considered as summarized in Table 3 –two sensible TES materials (rock and concrete) and two high temperature melting materials (Na_2SO_4 and $SrCl_2$) as phase change materials. The main results of the preliminary sizing are summarized in Figure 6, which reports the TES cost necessary to deliver the charging/discarding duty cycle of Fig 4, where epsilon is the void fraction of the TES packed bed.

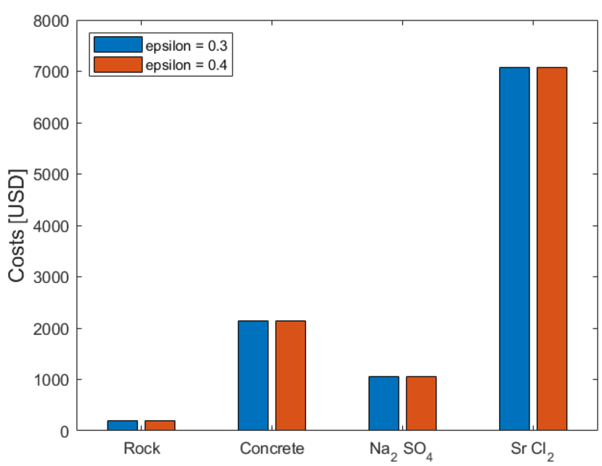

Fig 5: Thermal energy storage costs.

Interestingly, the Na_2SO_4 appears to be a competitive solution from an economic stand point, although confinement/corrosion challenges need to be addressed in a second stage of development.

4. CONCLUSIONS

In this work we combined experimental and numerical methods to address the integration of thermal energy storage with small-scale solar thermal Brayton (SSBC). The system is aimed at producing electricity in remote, off-grid rural areas. The experimental investigation carried out at Pretoria (South Africa), illustrates that steady state conditions can be reached within the SSBC process under nominal DNI. This ensures stables power output from micro turbine. However, numerical data illustrates that a minimum of 850-900 W/m^2 is required to operate the system. The DNI appears to exceed this value during a typical winter morning, allowing the possibility to store excess solar thermal energy. To this aim, a new SSBC configuration with TES system was proposed. A packed bed arrangement was considered along with four different possible types of storage materials. Quartzite rocks are most competitive from an economic stand point, although high temperature PCM (Na_2SO_4) might allow for smaller storage volumes but at the possible expenses of confinement and corrosion issues.

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