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Stirling engine based solar-thermal power plant with a thermo-chemical storage system

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ABSTRACT

This paper describes a solar-thermal run Stirling engine based uninterrupted power generating system employing magnesium sulphate impregnated Zeolite pellets for thermal energy storage. In the proposed system, Stirling engine design is based on the average temperature difference of 480 °C, assuming the heat sink temperature equal to the ambient temperature of that place. In presence of sun, Fresnel lenses of a specially designed hybrid capsule capture solar energy and concentrate them to provide necessary heat for the operation of the engine. In absence of the sun, required heat is provided by the thermo-chemical energy stored in Zeolite pellets. Working methodologies, modelling and simulation of the proposed system along with analyses of the obtained simulated results are presented in this paper. Possible performance of the scheme at different global positions for different period of a year has also been investigated.

1. Introduction

Electricity has become the fundamental necessity of modern world. More than 80% of electrical power is generated from fossil fuels [1]. The fixed reserve and the harmful effects of these conventional fuels have compelled researchers to think of alternatives. Scientists consider renewable energy resources as the best substitute of the trendy energy sources [2,3]. Amongst all the inexhaustible resources, solar energy is most abundant in terms of generating capability and a lot of work has been done to explore its potential on earth [4–7]. Most of the work, on solar energy for electricity generation, is based on photovoltaic (PV) with battery storage [2,8–11]. This paper presents a method of solar-thermal power generating system with thermo-chemical storage (magnesium sulphate impregnated Zeolite pellet). The thermo-chemical storage alleviates most of the shortcomings of traditional battery storage system like heavy weight, fixed life span, more charging time than discharging time, etc. In the proposed scheme, solar tracking system, which is an indispensable part of a PV technology, is replaced by a hybrid capsule consisting of glass and Fresnel lens reducing the complexity and additional energy consumption thereby decreasing expenses.

Stirling engine is the heart of the plant that converts the thermal energy in solar irradiance into mechanical energy. Stirling engine is an external combustion engine developed by Dr. Robert Stirling in 1816 [12,13]. It is a closed-cycle regenerative machine that operates on cyclic compression and expansion of the working fluid [13]. Stirling engine has higher thermal efficiency than Rankine cycle based system and is reported that it is cheaper than PV unit of small capacity [14]. Some other advantages of Stirling engine are multi-fuel capability, low noise, low fuel consumption, capability of using various fuel sources, etc. [15]. Due to the pronounced merits of Stirling engine, many researchers have shown interest in it. Can et al. [16] developed a Beta type Stirling engine using crank mechanism while, Aksoy and Cinar [17] performed theoretical investigation on kinematic and thermodynamic analysis of a beta type Stirling engine with rhombic-drive mechanism. Abbas et al. worked with dish Stirling technology with hydrogen as working fluid [18], on the other hand, Moghadam et al. [19] proposed a solar dish micro-combined heat and power (CHP) system and carried out its 3E (energy, environment and economic) based analysis. In [20], a delta-T Stirling engine have been developed and experimented by Boutammachte et al. under laboratory and field condition, conversely, an unconventional liquid piston Stirling engine pump was proposed by Van de Ven in [21] which was supposed to closely match the ideal engine cycle. Solmaz and Karabulut [22] explored the performance of a Stirling engine with a lever controlled displacer driving mechanism by comparing it with a rhombic-drive engine whereas, Karabulut et al. [23] carried out an experimental test on a similar system and presented the results. In the system, heat was supplied by liquefied petroleum gas (LPG) burner. The maximum power of 183 W was achieved with hot end

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Nomenclature

a	Stirling engine constant
AM	air mass
b	Stirling engine constant
c	Stirling engine constant
d	day of the year
D_x	phase angle (°)
EoT	equation of time (min)
HRA	hour angle (°)
I_s	solar irradiance (W/m^2)
L_a	total area of Fresnel lenses (m^2)
LT	local time
LST	local solar time
$LSTM$	local standard time meridian
M_g	mass of working gas (g)
n	engine speed (r.p.m)
P_e	engine pressure (kPa)
P_m	mean pressure (kPa)
P_o	output power of engine in one complete cycle (W)
R	working fluid constant (gas constant) (J/kg K)
s	Stirling engine constant
t	ratio of compression temperature and expansion temperature
TC	time correction factor (min)
T_c	fluid temperature of compression (°C)
T_e	fluid temperature of expansion (°C)
v	ratio of swept volume of compression and swept volume of expansion
V_{dc}	dead volume of compression space (cm^3)
V_{de}	dead volume of expansion space (cm^3)
V_r	regenerator volume (cm^3)
V_{sc}	swept volume of compression space (cm^3)
V_{se}	swept volume of expansion space (cm^3)
W_c	rejected thermal energy from the engine to environment (J)
W_e	indicated expansion energy i.e. input thermal energy from sun to the engine
W_i	indicated energy (J)
x	crank angle variation (°)
X_{dc}	ratio of dead volume of compression and swept volume of expansion
X_{de}	ratio of dead volume of expansion and swept volume of expansion
X_r	ratio of regenerator volume and swept volume of expansion
z	time (s)
α	elevation of sun (°)
δ	declination angle (°)
ϕ	latitude (°)
θ	zenith angle (°)

temperature of 260 °C and cold end temperature of 27 °C at speed of 600 rpm.

In the context of contemporary studies, the proposed scheme (depicted in Section 2) in the paper with some assumptions (Table 1) establishes a steady power output in diverse situations.

Stirling engine is driven by external heat and hence anything that can store thermal energy like water, rocks, concrete, pebbles, etc., can be used as backup source of heat for its operation. Amongst all the thermal storage system, chemical heat storage has the highest potential for long term storage [24]. Heat storage in the form of sensible and latent heat is the most studied technologies and is at an advanced state of development [25]. Thermal energy is stored in sensible heat storage by raising the temperature of the material. The storage density is then equal to the product of the specific heat of the material and the temperature change. On the other hand, Latent heat is the quantity of heat absorbed or released by a material, while changing its phase at a constant temperature. A phase change material (PCM) melts and takes up energy corresponding to the latent heat of the material when the temperature increases above the melting point. Conversely, the latent heat is released when the material is cooled back and the PCM solidifies. But sensible heat storage material and PCM progressively lose heat and are not suitable for long term storage which is undesirable especially for polar region [25]. Materials used for sorption storage have the highest storage density and some have even storage density near to that of Biomass [25]. Zeolites are alumina silicates that are considered to be most suitable for accumulation of heat by water adsorption–desorption process [26]. Natural Zeolites has lower performance compared to their synthetic counter parts [27]. Synthetic Zeolite has larger pore size, higher specific surface area [28] and higher operating temperature [26,28] with higher experimental energy storage density (124 kW h/m^3) [25]. Zeolites have proved to be a favourable porous expanded structure for magnesium sulphate ($MgSO_4$) with energy densities of 150–400 kW h/m^3 at a storage temperature compatible with solar-thermal collectors [24]. Whiting et al. [29], reported that impregnation of Zeolite Na–Y composite containing 15 wt% of $MgSO_4$ achieved highest heat of hydration (1090 J g^{-1}). $MgSO_4$ with water (H_2O) has energy density of 2.8 GJ/m^3 [24] and hence, $MgSO_4$ impregnated Zeolite pellet bed is considered as storage system for the plant.

Table 1
Assumptions made for system simulation.

Parameters	Assumptions
Hemisphere of the earth	Northern hemisphere
Longitude	92°E (fixed)
I_s	Depends on co-ordinates of the place and season
L_a	3 m^2
Rated capacity of Stirling engine	1.3 kW
Working fluid	Air
R	287 J/kg K
T_e	500 °C
T_c	Ambient temperature of the place
n	1500
x	0–360°
D_x	90°
V_r	0.2 cm^3
V_{se}	500 cm^3
V_{sc}	500 cm^3
V_{de}	0.2 cm^3
V_{dc}	0.2 cm^3
Storage system	$MgSO_4$ impregnated Zeolite pellet bed
Temperature of thermal energy released by storage system	500 °C
Efficiency of the alternator	80%

2. Methodology and description of the system

The block diagram of the plant is shown in Fig. 1.

The operation of the plant can be divided into three stages: Solar energy reception and concentration, conversion of thermal energy into mechanical energy and storage and release of solar-thermal energy.