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# Thermodynamic and economic investigation of a screw expander-based direct steam generation solar cascade Rankine cycle system using water as thermal storage fluid

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## HIGHLIGHTS

- Combination of DSG, cascade SORC and water-based storage is innovative.
- Optimum operating temperature of steam screw expander ranges below 250 °C.
- Thermo-economic comparison between direct and indirect systems is made.
- Compared with oil-based system, DSG system is more efficient.
- Cost of steel is less than one-third of the oil's.

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ABSTRACT

Solar electricity generation system (SEGS) which employs cascade steam-organic Rankine cycle (SORC) and steam screw expander (SE) is promising due to the high efficiency at moderate heat source temperature. This paper puts a special emphasis on heat storage and thermo-economic evaluation. Preferable operating temperature of the system is first clarified on the basis of SE characteristics. The temperature-dependent permissible stress of steam accumulator is modelled and the capital cost is investigated. Comparison between the direct steam generation (DSG) SEGS and an indirect one using thermal oil is made at a power capacity of 1 MW and storage of 6.5 h. The results indicate the DSG system has both thermodynamic and economic superiorities. The hot side temperature ($T_H$) of SORC generally does not exceed 250 °C to achieve an optimum solar thermal power efficiency. Given radiation of 750 W/m$^2$, the maximum efficiency ($\eta_{T,m}$) is 14.3% with a corresponding $T_H$ around 240 °C. The material cost of pressure vessels is 2.55 million RMB. For the indirect system, the optimal $T_H$ is about 230 °C and $\eta_{T,m}$ approximates to 13.2% and the estimated oil cost is 7.92 million RMB. It is recommended to adopt steam accumulators in the SE-driven SEGS.



## 1. Introduction

Screw expander (SE) is a volumetric machine used for the production of mechanical work in the power interval from several kW to a few MW. The functional characteristics of SE differ significantly from those of dynamic expanders (e.g. turbines). SE has high tolerance for two-phase working fluid and the fluctuation of heat source in a wide range of pressure, temperature and volumetric flow. It is able to start up and shut down quickly, and has no special warm-up, less faults from over-speeding and turning.

SE technology is promising in the low-medium temperature applications. The SE industry is at a stage for promotion in the world, with major industrial suppliers including Jiangxi Huadian Electric Power Co., Ltd, Opcon Group, Kaishan Ltd., Denair Group, ElectraTherm, Shanghai Hanbell Precise Machinery, Heliex Power Ltd. and QiyaoExpander Ltd. Products such as Opcon Powerbox WST (100–1600 kW) [1], HP145/HP204 (160–500 kW) [2], SEPG (300–3000 kW) [3], LGP510-S (750–2500 kW) [4], KE110V-50 (60–1000 kW), 6500-FL (110 kW) [5] and Denair ORC (10–300 kW or above) [6] are available on the markets. Isentropic efficiency of 75–80% is claimed for most products. The SE-based plants are gaining ever increasing interest as cost-effective sustainable energy systems.

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**Nomenclature**

| | |
|---|---|
| $A$ | aperture area, $m^2$surface area, $mm^2$ |
| $a$ | half long axis, mm |
| $b$ | half short axis, mm |
| $C$ | total cost, RMB |
| $D$ | diameter, mm |
| $G$ | solar radiation, $W/m^2$ |
| $g$ | gravity, $m/s^2$ |
| $H$ | height, mm |
| $h$ | enthalpy, kJ/kgedge height of head, mm |
| $M$ | mass, kg |
| $m$ | mass flow rate, kg/s |
| $P$ | cost per kilogram, RMB/kg |
| $p$ | pressure, MPa |
| $r$ | ratio |
| $T$ | temperature, °C |
| $V$ | total volume, $mm^3$ |
| $v$ | specific volume, $cm^3/kg$ |
| $W$ | power output, kW |
| $\delta$ | thickness, mm |
| $\varepsilon$ | device efficiency |
| $\phi$ | welding coefficient |
| $\gamma$ | isentropic index |
| $\eta$ | system efficiency |
| $[\sigma]^t$ | permissible stress, MPa |
| $\rho$ | density, $kg/m^3$ |

*Abbreviation*

| | |
|---|---|
| DSG | direct steam generation |
| HTF | heat transfer fluid |
| HX | heat exchanger |
| ORC | organic Rankine cycle |
| P | pump |
| PCM | phase-change material |
| PTC | parabolic trough collector |
| SE | screw expander |
| SEGS | solar electricity generation system |
| SORC | steam-organic Rankine cycle |
| SRC | steam Rankine cycle |
| V | valve |

*Subscripts*

| | |
|---|---|
| I | Cycle I |
| II | Cycle II |
| 0 | reference state |
| 1–8 | state points |
| *a* | ambient |
| *b* | binary phase/beam/built-in |
| *C* | cold side |
| *ch* | characteristic |
| *cy* | cylinder |
| *F* | friction |
| *g* | generator/static |
| *H* | hot side/hour |
| *head* | elliptical head |
| *i* | diagram |
| *in* | inlet |
| *L* | leakage |
| *l* | liquid phase |
| *M* | mechanical |
| *m* | maximum |
| *net* | net |
| *oil* | oil |
| *op* | optimum |
| *os* | overall isentropic |
| *out* | outlet |
| *P* | peak |
| *p* | pressure/pump |
| *pp* | pinch-point |
| *S* | shaft |
| *s* | storage/isentropic/steam |
| *steel* | steel |
| *su* | supply |
| *T* | thermal/turbine |
| *t* | total mass flowrate |
| *TD* | diagram |
| *Th* | theoretical |
| *TI* | isentropic |
| *TM* | thermodynamic |
| *v* | volume |
| *w* | water |

Solar electricity generation system (SEGS) holds a potential market for SE [7–10]. SEGS using steam SE avoids superheat at the expander inlet [11]. Direct steam generation (DSG) in the parabolic trough collectors (PTCs) can be facilitated. The system can work at lower temperature than steam turbine-driven ones without remarkable decrement in the efficiency. The technical requirement in solar energy collection is thus reduced. Coupling with a bottom organic Rankine cycle (ORC), the SE does not need to experience highly off-design operation [12–14], and the SEGS can perform better at low ambient temperature. It is especially suitable for distributed cogeneration applications. Fundamentals, advantages and some thermodynamic results of the SEGS using cascade steam-organic Rankine cycle (SORC) at constant SE efficiency have been presented previously [15].

Heat storage is a key subject in solar thermal electricity generating systems. The proposed SEGS is appreciated only if the issues related with storage can be easily addressed. Similarly with steam turbine-driven systems, there are many alternative materials for thermal storage of the SE-based SEGS, including molten salt, thermal oil and water.

Molten salts were adopted for thermal energy storage in Themis solar power plant in 1983. Salts composed of $NaNO_3$ ($w_t$ = 60%) and $KNO_3$ ($w_t$ = 40%) were chosen as storage mediums of Solar Two in 1995 [16]. Molten salts acting as the heat transfer and storage fluid were further employed in Solar Tres power plant built in 2008 [17]. After a long-term development, molten salt technology represents one of the most flexible, efficient and cost-effective large-scale solar energy storage technologies nowadays and is being deployed in many plants such as 280 MW Solana Generating Station and Ivanpah concentrating solar power plant.

Thermal oil was used for storage in the first SEGS plant (SEGS I) in 1984. It was filled into two different tanks: a hot tank, where the oil was stored after being heated to 307 °C by the collectors, and a cold tank, where the oil was kept at about 240 °C after releasing its energy to the Rankine cycle [18,19]. This storage technology was found to be successful for helping the plant dispatch its electricity generation during non-sunlight periods. Another benefit was that oil could be utilized as heat transfer fluid. Because thermal stability of commercial thermal oil could be guaranteed only when the working temperature ranged below 395 °C, this storage concept no longer appeared in later, more efficient SEGS plants.

Water was especially suitable to meet the requirements for buffer storage in solar steam systems. Pros and cons of steam accumulator for thermal storage of conventional turbine-driven