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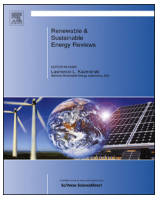

Thermodynamic performance evaluation of solar and other thermal power generation systems: A review

M.K. Gupta [a], S.C. Kaushik [b], K.R. Ranjan [b], N.L. Panwar [c], V. Siva Reddy [d,*], S.K. Tyagi [e]

[a] *Ujjain Engineering College, Ujjain 456010, Madhya Pradesh, India*
[b] *Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India*
[c] *Department of Renewable Energy Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur 313001, Rajasthan, India*
[d] *Sardar Patel Renewable Energy Research Institute, Vallabh Vidhyanagar 388120, Gujarat, India*
[e] *Sardar Swaran Singh National Institute of Renewable Energy, Jalandhar-Kapurthala Road, Wadala Kalan, Kapurthala 144601, Punjab, India*

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ABSTRACT

In this communication, detailed review of the solar thermal power plants based on the available solar concentrator systems like parabolic trough, parabolic dish, central tower, linear Fresnel reflector system are reported. The aim of the paper is to summarize overall research work being carried out worldwide on the thermodynamic performance evaluation of solar and other thermal power generation systems using different thermodynamic cycles. An attempt has also been made to assess as well as compare the energetic and exergetic performance of such thermal power generation systems. It has been observed that the efficiencies of the solar concentrator aided coal fired thermal power plant, and combined-cycle power plants are higher as compared to a solar alone thermal power plants. Furthermore, there is much scope in the areas of solar aided thermal power generation for further research with the aim of quantifying energy and exergy losses, and exergy destructions in the components of the solar thermal power generation systems.

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1. Introduction

Owing to exponential population growth, rapid industrialization, urbanization, modernization and improvement in the standard of living, the global electricity consumption is expected to increase

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* Corresponding author. Tel.: +91 9898722118.
E-mail address: vundelaap@gmail.com (V.S. Reddy).

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significantly in coming years [1]. Extensive use of coal and other fossil fuels have led to pile of an enormous amount of carbon dioxide in the earth's atmosphere and a resultant global warming [2]. Increase in the capacity of the hydro power plants; however, needs building of large water storages. There is a limitation on building water storages, as they involve heavy cost, submerging of large-area, disturbing existing ecological balance, etc. Increase in the capacity of electricity generation through other renewable energy sources is a matter of further research and development. Presently, the maximum demand of electricity is met by the thermal power generation systems. Any modifications in the existing thermal power plants to increase the electricity generation capacity by the utilization of renewable-energy sources can lead to sustainable growth in the power production capacity. Among the renewable-energy sources, solar energy is one of the cleanest forms of energy resources and considered as a green source of energy available abundantly. Similar to fossil fuels and nuclear energy, solar thermal energy (solar heat) can be transformed into electricity by the thermodynamic process, which is of the highest importance in the present situation. Electricity generation thermal systems added with solar energy source release very low carbon to the environment and have less payback time. The power generation from it seems most promising and viable option for the present and future [3,4].

In this paper, detailed review of the solar thermal power plant based on the available concentrator technologies like a parabolic trough, parabolic dish, central tower, linear Fresnel reflector system are reported. It provides useful knowledge and aids in development of solar electricity generation for different climatic conditions.

This review is presented here with the aim to summarize overall research work being carried out worldwide for solar thermal power generation using different generation routes and thermodynamic cycles. An attempt has also been made to assess as well as compare the energetic and exergetic performance of such thermal power generation systems.

2. Performance evaluation through energy and exergy analysis

These days, need of improving the efficiency of existing thermal power generation systems as well as the systems under design and a development stage has been felt for effective utilization of energy resources. Energy and exergy analysis are thermodynamic tools to evaluate and better understand the performance of power generation systems. It also helps in identifying the components and processes where there is more possibility of improvement.

Normally, performance evaluation of thermal power generation system is performed using the concept of the first law of thermodynamics (i.e. through energy analysis). It is found to be inadequate, and more meaningful evaluation must include second law analysis (i.e. exergy analysis). The second law analysis is based on law of degradation of available energy, i.e. quality of energy which is the more realistic, rational and true measure of the deviation of an actual system from the ideal system.

The first law gives no distinction between heat and work, no provision for quantifying the quality of heat, no accounting for the work lost through a process and no information about the optimal conversion of energy [5,6]. The second law of thermodynamics applied in the form of exergy balances for components and processes can locate and quantify the irreversibilities which cause loss of work and inefficiency in thermal systems. Identifying the main sites of exergy loss shows the direction for potential improvements. The principles and methods of exergetic analysis are well established [6–11]. Many of the analyses might be more effective if a greater prominence is given to the exergetic analysis [12]. The second law analysis provides the tool for clear distinction between energy losses to the environment and internal irreversibilities in the process [13,14].

The aim of exergetic analysis is to perceive and to evaluate quantitatively the effect of irreversible phenomena which increases in the thermodynamic imperfection of the considered process [15,16]. The optimal design criteria for any thermal system can be achieved by maximizing the exergy output/exergy efficiency of the system or by reducing the irreversibility of the system [12]. Thermodynamically there is a direct relationship between the irreversibility of the process and the amount of useful work dissipated during the process [8].

Exergy is maximum work potential which can be obtained from a form of energy [8,9,12]. The exergy losses have a significant effect on environmental impact and can be used as a criterion for assessing the depletion of natural resources [15]. Thermodynamic assessment of any system is incomplete, unless the exergy concept becomes a part of the analysis [15,17,18–24]. Exergy is a generic term for a group of concepts that define the maximum work potential of a system, a stream of matter or a heat interaction; the state of the (conceptual) environment being used as the datum state. In an open flow system, there are three types of energy transfer across the control surface, namely work-transfer, heat-transfer, and energy associated with mass transfer or flow. The work transfer is equivalent to exergy in every respect as exergy is maximum work which can be obtained from that form of energy.

The exergy of heat transfer Q from the control surface at temperature T_k is determined from maximum rate of conversion of thermal energy to work $W_{\max}$. The $W_{\max}$ is given by

$$W_{\max} = Q\left(1-\frac{T_a}{T_k}\right) \tag{1}$$

Exergy of the steady flow stream of matter is sum of kinetic, potential and physical exergy. The kinetic and potential energies are again equivalent to exergy. The physical specific exergy Ψ depends on initial state point of matter and environmental state and is given by

$$\Psi = \dot{m}\left[\left(h^0 - h_a^0\right) - T_0(s - s_a)\right] \tag{2}$$

$$h^0 = h + \frac{C^2}{2} + gZ \tag{3}$$

The subscript a refers to the environmental state, h is specific enthalpy; s is specific entropy and T_a is environmental/ambient temperature.

Energy analysis is based on the first law of thermodynamics, which is related to the conservation of energy. Exergetic analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy systems. Exergetic analysis is a useful method to complement, but not to replace energy analysis. Unlike the mass and energy, the exergy is not conserved. The first law of thermodynamics or energy balance for steady flow process of an open system is given by

$$\sum \dot{Q}_k + \dot{m}\left(h_i + \frac{C_i^2}{2} + gZ_i\right) = \dot{m}\left(h_o + \frac{C_o{}^2}{2} + gZ_o\right) + \dot{W} \tag{4}$$

where Q_k heat transfer to system from source at temperature T_k, and W is the network developed by the system. The other notations C is the bulk velocity of the working fluid, Z is the altitude of the stream above the sea level, g is the specific gravitational force.

The exergy balance for steady flow process of an open system is given by

$$\sum\left(1-\frac{T_a}{T_k}\right)\dot{Q}_k + \sum_{in} \dot{m}\Psi_i = \dot{E}x_W + \sum_{out} \dot{m}\Psi_o + \dot{I} \tag{5}$$

where Ψ_i and Ψ_o are respectively the exergy associated with mass inflow and outflow, is $\sum(1-(T_a/T_k))\dot{Q}_k$exergy associated with heat transfer, $\dot{E}x_W$ is exergy associated with work transfer and I is