Energy 80 (2015) 414–427

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergy analysis and annual exergetic performance evaluation of solar hybrid STIG (steam injected gas turbine) cycle for Indian conditions

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ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form
28 November 2014
Accepted 1 December 2014
Available online 27 December 2014

Keywords:
Solar STIG cycle
Steam injection
Exergetic performance
Gas turbine

ABSTRACT

The STIG (steam injected gas turbine) cycle offers a way for increasing the power, efficiency and NO_x reduction in gas turbines by injecting steam into the combustor. The present exergetic study is to investigate the influence of compressor PR (pressure ratio), TIT (turbine inlet temperature) and SAR (steam to air ratio) on the solar hybrid STIG cycle. Exergy analysis was performed for four cases based on the parameters of real gas turbines. Annual exergetic performance is also presented for the sites Indore and Jaipur in India under constant and variable power modes. The analysis suggests that the steam injection does not affect the performance of compressor. The total exergy destruction in the cycle increases with SAR and TIT. The exergetic efficiency also increases in the range of 40%–54.2% with SAR up to 0.9. The magnitude of exergy destruction in all components in the cycle (except compressor) increases by increasing SAR. Nevertheless, largest component of exergy destruction in the combustion chamber increases with SAR and TIT about 53% at SAR 0.9. The exergetic efficiency of combustor increases from 74.5% to 81.8% with increasing SAR from 0.3 to 0.9. The exergy destruction in the turbine increases considerably with compressor pressure ratio, sparingly with SAR and independent of TIT. The exergy destruction in the SH (super heater) is less compared to the economiser in the HRSG (heat recovery steam generator). The contribution of solar energy (exergetic solar fraction) is more sensitive to TIT and SAR than PR. It is noticed that increase in turbine outlet temperature, led by PR and TIT, decreases the exergetic solar fraction, and the cycle exergetic efficiency improves as the exergetic solar fraction increases, which leads to an improved performance device. The second largest percentage of exergy destruction is in the flue gas condenser to recover water for recycling, and the heat removed from the condenser is lost to the surroundings by cooling air. The annual values of exergetic solar fraction and exergetic efficiency at Indore are higher than Jaipur in both constant and variable power modes of operation.

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1. Introduction

Electric power generation, in India, is an important issue today and is the backbone of economic development of the country. In many parts of the world, gas turbines with new technologies are being used at peak and base load power plants to meet the rapidly growing energy demand. Power production from solar energy is intermittent and high cost of solar thermal systems makes sense only in regions with high solar insolation. The idea of a hybrid system is to provide higher availability of the plant by allowing stable operation even in periods of low irradiation, which also translates into better financial conditions for the plant. In regions of lower solar availability, hybrid systems could help in making use of the available solar radiation by providing stable operation conditions and reducing fossil fuel consumption. Steam injection concept has been practiced since 1980's for power augmentation, NO_x, CO_2 reduction and to cool the blades more effectively than air. The aero derivative gas turbines for power generation are being used with minor modifications to operate the STIG (steam injected gas turbine) as base load plant.

M. Livshits and A. Kribus [1] described that in the conventional STIG, the flow rate of steam is limited by the amount of thermal energy available at the HRSG (heat recovery steam generator) from

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http://dx.doi.org/10.1016/j.energy.2014.12.001
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the turbine exhaust stream. If an additional heat source is available, then larger amounts of steam could be injected into the cycle. In the solar STIG cycle, the additional steam is provided from solar concentrating collectors, producing a hybrid cycle with heat input from both solar collectors and from fuel in the combustor (Fig. 1). Solar heat is used mainly for evaporation. Recuperation of gas turbine waste heat is assigned primarily for super heater and economizer, to avoid the thermodynamic irreversibility and loss of work potential due to large temperature differences. The solar steam for the hybrid STIG cycle should match the turbine pressure, typically in the range of 10–30 bar, corresponding to saturated steam temperatures of 180–234 °C. These pressures and temperatures are lower than those of current solar power plants and can be easily achieved with lower cost versions of linear concentrators such as parabolic trough and linear Fresnel collectors.

Exergetic analysis is a qualitative thermodynamic assessment of any power generation system. In the last several decades, exergy analysis has begun to be used for system optimization. The method of exergy analysis (availability analysis) based on the second law of thermodynamics enables the location, cause, and true magnitude of energy resource waste and loss to be determined and also provides component efficiency. Such information can be used in the design of new energy efficient systems and for improving the performance of existing systems. Exergy analysis also provides insights that eludes a purely first law approach [2]. Therefore, it is essential to study the solar STIG cycle based on the second law analysis of thermodynamics. The exergy analysis is applied here to the thermodynamic cycle excluding the solar collector field.

Many researchers have performed the exergetic analysis of fossil fuel and renewable energy based power generation systems. The outcomes of second law based analysis of gas turbine plant, generally pertaining to steam injected gas turbine components are recapitulated in this section. M. Jonssona and J. Yan [3] summarized the description of available commercial steam injected gas turbines and highlighted the research and development in the modified steam injected gas turbine cycles including intercoolers, recuperators, reheat or topping steam turbines and cogeneration investigated by many researchers. D. P. S Abam and N. N. Moses [4] investigated the second law efficiencies of the 33 MW gas turbine plant and the combustion chamber are found to decrease more significantly with increase in the ambient temperature than the air compressor and the gas turbine. Yaser Sahebi and Hasan Athari [5] studied the irreversibility of compressor, combustion chamber and turbine decreases in the gas turbine cycle with steam injection and inlet fogging cooler and compared that the second law efficiency of STIG cycle is more than both the simple gas turbine cycle and steam injected gas turbine with inlet fogging cooler at 45 °C ambient temperature and 15% relative humidity. R. Layi Fagbenle et al. [6] indicated that the exergy loss in the combustion chamber is largest at about 79% of the total system exergy loss and the exergy defect associated with the steam injection is only 1.3% of the total exergy loss, and is not excessive for the 53 MW (net) biogas fired integrated gasification steam injected gas turbine (BIG (biomass integrated gasification)/STIG) plant based on the LM 5000 aero derivative gas turbine.

F.J. Wang and J.S. Chiou [7] analysed a retrofitted simple cycle GENSET (cogeneration) with GE Frame 6B and presented that the exergy efficiency of combustor is 76% which is higher than that of HRSG about 62%. Besides, the power output of STIG cycle is less sensitive to ambient temperature than that of a simple cycle. They also studied the STIG with inlet air cooling using Taipower's Frame 7B simple cycle GENSET that the effect of the STIG is more profound than that of the IAC (inlet air cooling) in improving the power output and efficiency. The exergy loss per MW output, the system with both the STIG and IAC feature is 23.7% lower than that of the basic system [8]. T. Srinivas et al. [9] investigated that the major percentage of exergetic loss that occurs in combustion chamber decreases from 38.5% (without steam injection) to 37.4% (3 kg steam/kg fuel) with introduction of steam injection into the combustion chamber for a STIG based combined cycle. Mustafa Zeki Yilmazoglu et al. [10] examined the effect of steam injection mass flow rate, duct burner exhaust temperature on the combined cycle power plant in Turkey using GE7251FB model gas turbine-generator with 373 MW electrical power (in ISO conditions), CMI model heat recovery steam generator and ALSTOM steam turbine generator with 92.26 MW electrical power, and found that the duct burner exit temperature and steam injection mass flow rate to the combustion chamber decreases the exergy efficiency from 50.52 to 50.02% due to additional fuel consumption and a bled steam from HP turbine is injected into the combustion chamber to improve the net power and minimize the NO_X emissions of the power plant. Sadegh Motahar and Ali Akbar Alemrajabi [11] evaluated that the overall exergetic efficiency calculated for the base solid oxide fuel cell and steam injected gas turbine hybrid power system is 58.28% and steam injection boosts the exergetic efficiency by 12.11%.

K. Nishida et al. [12] analysed that the exergy efficiency of the regenerative STIG with steam injection after the compressor is higher than that of the simple, regenerative gas turbine cycle, regenerative cycle with water injection before and after compressor, STIG and regenerative STIG with steam injection into

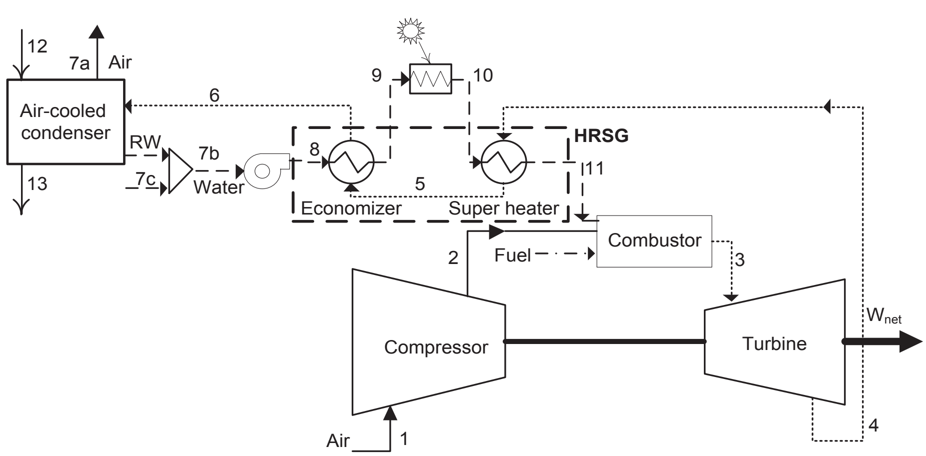

Fig. 1. Layout of the solar hybrid STIG cycle.

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