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Research Article

Improving Energy Efficiency in Gas Turbine Systems: The Role of Solar Collectors

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ABSTRACT

Energy sector growth is almost entirely proportional to the gross development of a nation. However, one of the most difficult problems facing the energy sector today is the rapid exhaustion of traditional energies. To solve this problem, the combination of modern equipment with renewable sources of energy has begun to receive increasingly more attention. Increasing fuel efficiency is an approach that is far more environmentally friendly, as it aids in preserving energy resources and decreasing emissions, thus playing a large role in reducing greenhouse gases.

This study investigates how solar tower collector systems can be utilized to improve the characteristics of modern gas turbine plants. Having the solar power integrated into gas turbine systems enables an improvement in performance and sustainability. The utilization of concentrated solar power to preheat the working fluid can lower fuel consumption, thus increasing the thermal efficiency of the system. Furthermore, the integration of solar energy into traditional electricity generation begs a solution to the intermittency challenges associated with renewables. This method not only lessens dependence on fossil fuels but also supports the global shift toward cleaner energy solutions. The results of this study demonstrate that integrating solar power with gas turbines is a practical and effective step toward a more sustainable energy future.

Keywords: Energy saving, heat supply, fuel type, centralized control, waste heat, heat losses, energy efficiency, solar power, radiation, gas reserves, convection.

1 INTRODUCTION

The three main sources of renewable energy on Earth are geothermal heat, orbital gravity forces, and solar radiation. The most prevalent and prolific of these is solar energy. The Earth's atmosphere receives about 1.7×10^{17} W of energy from the Sun [1]. About 70% of this energy reaches the surface of the Earth, with the rest reflected back into space. The harnessing of solar energy is pretty small considering variable factors such as atmospheric conditions, geographical location, and time-of-day variations which influence the quantity of the energy available at a given moment. Despite the disadvantages, however, even only one minute of this incoming radiation can provide enormous amounts of electrical energy, illustrating the huge scope for its acceptance into conventional sources of energy.

In Uzbekistan, its energy sector is characterized by a high dependence on natural gas, with over 85% of the country's overall electricity production [3]. Despite such a

traditional source of energy contributing towards securing energy, the country is facing a range of complications, such as depletion of natural gas reserves, price fluctuations in fuel, and environment-related concerns. The burning of fossil fuels in a gas turbine releases high volumes of carbon dioxide (CO_2), contributing to high levels of air pollution and accelerated climate change. As a result, increased demand for energy, together with a quest for cleaner alternative sources, creates a demand for new approaches focused on efficiency improvement and reduced use of non-renewable sources of energy.

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A contemporary technological development involves combining solar energy systems with gas turbine technology. Installation of a solar tower collector enables sunlight to be concentrated, and then it raises the temperature of compressed air before it enters a combustion chamber. This technology stands out through its ability to save fuel, maximize thermal efficiency, and minimize greenhouse gas emissions. According to studies, integration of compressed air heating through solar driving can yield a 20% improvement in overall efficiency in relation to gas turbines, accompanied by a drop in CO_2 emissions over 30% [3]. In addition, such a hybrid technology is in consonance with Uzbekistan's renewable development objectives, with an objective of generating at least 25% of country's electricity through renewable sources in 2030 [3].

2 THE SUN AS AN ENERGY SOURCE

The Sun itself is just like a big blackbody, having a surface temperature of about 5777 K. Inside this enormous sphere, powerful thermonuclear reactions facilitate the generation of energy, with the temperature increasing from 8 million K to 40 million K in different regions. The vast thermal energy produced within the Sun is transferred to the surface, where it is then radiated into space.

An examination of the Sun's interior reveals three principal regions: the core,

June 14

Time, h	5^{00}	6^{00}	7^{00}	8^{00}	9^{00}	10^{00}	11^{00}	12^{00}	13^{00}	14^{00}	15^{00}	16^{00}	17^{00}	18^{00}	19^{00}	20^{00}
DNI, W/m^2	62	227	418	603	766	891	963	984	951	857	723	52	283	182	12	0

July 14

Time, h	5^{00}	6^{00}	7^{00}	8^{00}	9^{00}	10^{00}	11^{00}	12^{00}	13^{00}	14^{00}	15^{00}	16^{00}	17^{00}	18^{00}	19^{00}	20^{00}
DNI, W/m^2	34	142	371	557	722	850	907	934	909	846	721	557	368	179	30	0

Figure 1. Direct normal irradiation for Tashkent for June /July 14

the radiation zone, and the convective zone. The core constitutes roughly 23% of the Sun's radius and is the site where approximately 90% of the total energy of the Sun is generated. Moving further out to the radiation zone, which extends to as much as 70% of the Sun's radius, the temperature drops to around 13,000 K. Adjacent to this zone lies the convective zone, where temperatures drop even further, ultimately reaching some 5,000 K at the Sun's surface.

To analyze the integration of central solar heaters with the existing gas turbine plant at the Tashkent CHP, it is first necessary to study the solar radiation in this area. Tashkent, like many regions of the country, is considered favorable for the use of solar energy due to the high number of sunny days. Figure 1 shows the hourly solar radiation on two summer days (June 14 and July 14, 2019) chosen to represent typical high radiation conditions, which shows that solar radiation is high for a long time during the day.

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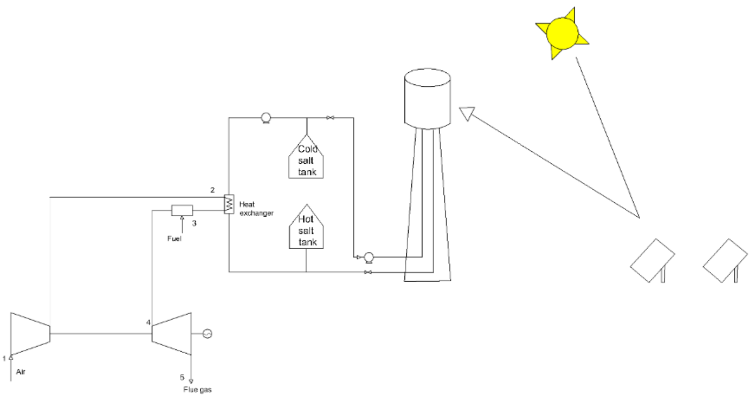

Figure 2. Schematic diagram of the integrated central solar receiver gas turbine system

3 PERFORMANCE AND ENERGY BALANCE OF SOLAR-ASSISTED CHP SYSTEMS

This chapter develops a thermodynamic model of a hybrid gas turbine system integrated with solar energy. The main focus of the model is to heat the compressed air using the heat coming from the solar tower, thereby increasing the efficiency of the system. The analysis is based on the law of conservation of energy, the first and second laws of thermodynamics. The operation of the gas turbine system using solar heat, the changes in temperature, pressure and heat flows, as well as the effect on efficiency are mathematically considered.

3.1 ENERGY BALANCE OF THE GAS TURBINE AND AIR–MOLTEN SALT HEAT EXCHANGER LOOP

To carry out the thermodynamic evaluation of a solar-hybrid gas turbine system, energy balance equations are initially formulated for the key components — the compressor, solar receiver, combustion chamber, and turbine. As the system starts with the compression of ambient air by the compressor, the analysis begins with determining the compressor's power requirement, since the pressure and temperature of the compressed air have a significant impact on the performance of the entire cycle. The compressor's energy demand is calculated using the following expression:

$$W_c = \mathrm{m}_a(h_2 - h_1)$$

where:

m_a — mass of air (kg)

h_1 — ambient air enthalpy (kJ/kg)

h_2 — compressed air enthalpy (kJ/kg)

The work generated by the gas turbine is calculated using the following equation:

$$W_t = (\mathrm{m}_a + \mathrm{m}_f)(h_3 - h_4)$$

where:

m_f — mass of fuel (kg)

Total work output:

$$W_{\text{cyc}} = W_t - W_c$$

Heat added to system by heat exchanger:

After the compressed air leaves the compressor, it is further heated in a secondary heat exchanger, where it receives thermal energy from molten salt heated by solar radiation. The amount of heat transferred to the compressed air is calculated based on using the following equation:

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$Q_{2,3} = m_a(h_3 - h_2)$

where:

h_3 — compressed air enthalpy after heat exchanger (kJ/kg).

Heat added to the system by combustion chamber:

$$Q_{3,4} = m_f \cdot LHV_{\text{fuel}} = (m_a + m_f)(h_4) - m_a h_3$$

where:

LHV_{fuel} — lower heating value of fuel (kJ/kg)

h4 — flue gas enthalpy (kJ/kg)

Tus, the total cycle efficiency is determined by equation:

$$\eta_{\text{cyc}} = W_{\text{cyc}}/(Q_{2,3}+Q_{3,4})$$

The above efficiency equation is complicated by the fact that two different heat sources are combined and must be treated equally. Here, although fuel and sunlight are both high-quality energy sources, only fuel consumption is related to the cost, and once the construction work is completed, the use of sunlight is completely free. In addition, the energy in the fuel is already accumulated and can be directly fed into the gas turbine, while solar energy is relatively diffuse and must be collected, concentrated, and converted into heat before it can be used.

Therefore, it is appropriate to calculate the fuel-electricity efficiency of the system using the equation below.

$$\eta_{\text{cyc}} = W_{\text{cyc}}/m_f \cdot LHV_{\text{fuel}}$$

or

$$\eta_{\text{cyc}} = W_{\text{cyc}}/((m_a + m_f) \cdot h_4 - m_a \cdot h_3)$$

As can be seen from the above equation, the efficiency of the system improves with a decrease in fuel consumption or an increase in the enthalpy at state 3 (h_3).

3.2 CENTRAL SOLAR RECEIVER

The received solar input is calculated as the product of the receiver area, its absorptivity a_r and the average flux over the receiver. The average flux at the receiver is in turn, related to the solar irradiance through the optical efficiency and geometric concentration ratio.

$$Q_{sol} = A_r \cdot \alpha_r I_r = A_r \cdot \alpha_r \eta_{\text{opt}} \, CR_g I_b$$

Where:

A_r — receiver area [m^2]

I_r — average flux over the receiver [W/m^2]

η_{opt} — optical efficiency

CR_g — geometric concentration ratio

I_b — solar beam [W/m^2]

As shown equation below, in the receiver losses are divided into to types, radiation losses and convective losses:

$$Q_{loss} = A_r \cdot (\varepsilon_r \sigma (T_r^4 - T_a^4) + h_{\text{loss}} (T_r - T_a))$$

Where:

ε_r — receiver emissivity

σ — Stefan–Boltzmann constant [$W/m^2 \cdot K^4$]

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T_r — receiver temperature [°C]

T_a — ambient temperature [°C]

h_{loss} — convection heat loss coefficient [W/m²· K]

The operating temperature at which solar energy can be effectively harnessed in the system is determined by the energy balance between the incoming solar thermal power to the receiver (Q_{sol}), the useful extracted thermal power (Q_{use}) and the thermal losses from the system (Q_{loss}). This is mathematically expressed by following equation:

$$Q_{sol} = Q_{use} - Q_{loss}$$

4. SIMULATION OF OVERALL CYCLE

The simulation of the Tashkent CHP considered in this study was developed in a previous work, and the parameters of the gas turbine plant were as follows.

The following baseline parameters were employed in the simulation:

- T_1 (Ambient air temperature): 15°C
- T_2 (Compressed air temperature after the compressor): 404.6°C
- P_2 (Compressor outlet pressure): 1.55 MPa
- T_4 (Exhaust gas temperature from combustion chamber): 1171.4°C
- W (Gas turbine net power output): 28.1 MW

Based on above parameters comprehensive simulation of the total cycle was conducted to assess the potential energy efficiency improvements by integrating solar collectors with gas turbine systems. The simulation framework was designed to model the thermodynamic behavior of the hybrid system under different operating conditions, taking into account the variability of solar input, turbine performance characteristics, and the interaction of auxiliary components.

The main assumptions made in the simulation include:

- Constant ambient conditions (standard atmospheric pressure and temperature);
- Stable operation of the gas turbine and solar collector system;
- Negligible heat losses in piping and storage;
- Perfect tracking of the sun by the solar collectors to maximize solar energy.

The simulation was performed using Matlab, which allows for dynamic modeling of temperature, pressure, and flow parameters throughout the cycle. The effect of diurnal variations in solar radiation on the system efficiency was studied.

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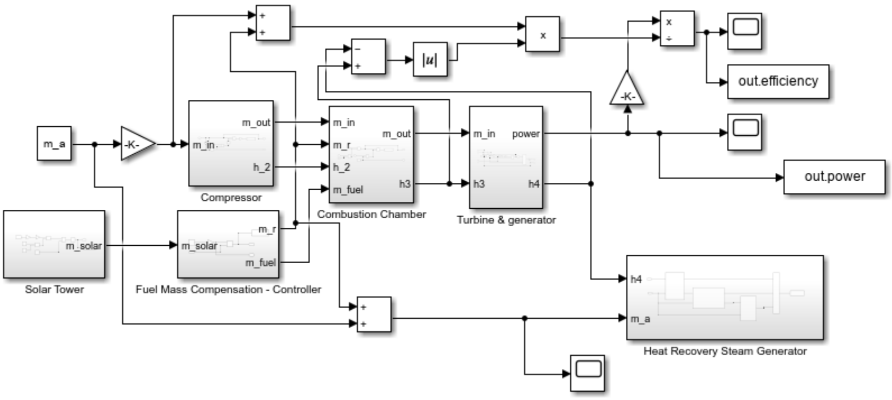

Figure 3. MATLAB simulation of a solar tower heater integrated with a gas turbine system

Figure 4. Hourly variation of solar radiation throughout the day

Figure 4 shows the hourly variation of solar radiation during a typical day. As can be seen, solar radiation starts to increase in the early morning, peaks around noon, and decreases towards evening, which is consistent with the expected solar energy profile for the Tashkent region. This pattern directly affects the thermal contribution of the solar tower, and consequently the fuel savings and system efficiency.

Based on the solar radiation profile, the system behavior was simulated at different times of the day. The output data included the following changes:

Fuel consumption (Figure 5), which showed a clear decrease during the hours of high solar energy input;

Improved overall thermal efficiency due to the reduced demand on the combustion system by solar preheating;

Turbine performance parameters that remained within operating limits by utilizing additional thermal energy.

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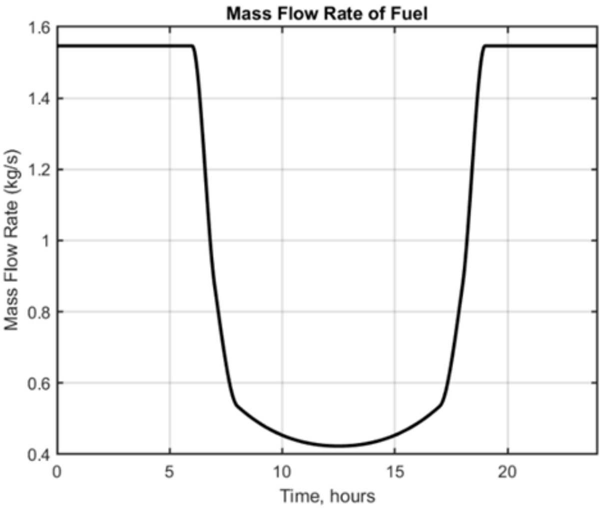

Figure 5. Hourly variation of fuel consumption as a function of solar radiation

In addition, during periods of high solar input, a significant reduction in CO_2 (Figure 6) emissions was observed due to reduced fuel consumption.

5. CONCLUSION

This study explored the potential for improving the energy efficiency of gas turbine systems through the integration of solar thermal energy, with a focus on a real-world case study of the Tashkent CHP plant. A dynamic simulation model developed in MATLAB was utilized to evaluate the operational behavior of the hybrid system under varying solar input conditions.

The results of the simulation indicate that the addition of a solar tower heater significantly reduces fuel consumption during daylight hours, particularly when solar irradiance is at its peak. This reduction in fossil fuel use contributes not only to enhanced thermal efficiency (Figure 7) but also to a corresponding decrease in carbon dioxide emissions, underscoring the environmental advantage of solar-assisted gas turbine configurations.

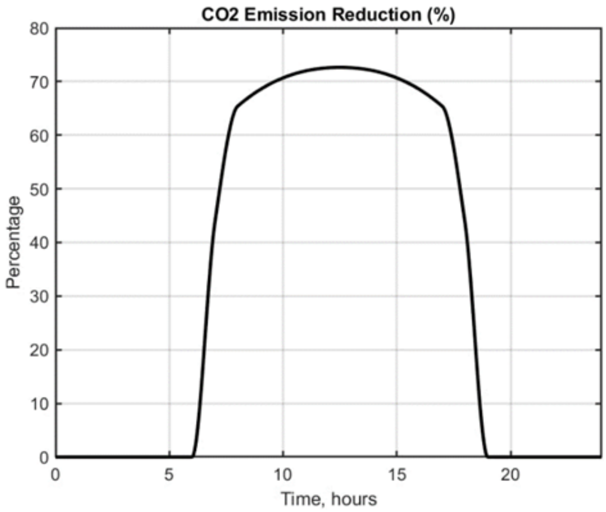

Figure 7. CO2 emission change over the day

Moreover, the system's responsiveness to hourly solar variation confirms the importance of optimizing solar integration for locations with strong solar availability, such as Tashkent. These findings support the feasibility and effectiveness of hybrid CHP systems and provide a foundation for further research into improving their performance through solar technologies.

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