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THERMAL ANALYSES INSTALLED RECEIVERS IN SOLAR-HYBRID GAS TURBINES

Z.M. Mukhiddinov,

J.A. Normuminov,

T. Mirzaabdullayev

Ushbu maqolada, kombinatsiyalashgan siklli stansiya (KSS)larida kompressordan chiqib gaz turbinasiga kiruvchi havoni quyosh nuri qabul qilgichlari orqali qizdirib mavjud gaz turbinalarni gibridlash ko'rib chiqiladi. Kontseptsiya quyosh nurlarini harakatlanuvchi oynalar orqali yig'ish va ularni qabul qilgichga jo'natib, natijada energiya ishlab chiqarishda yuqori effektivlikka erishishni o'z ichiga oladi.Bu yondashuvni boshqa issiqlik stansiylari konsepsiyasidan afzalliklari ko'rib chiqilgan. Maqola shuningdek nur qabul qilgichni dizayni va boshqa muammolarni ko'rib chiqadi, ayniqsa gaz turbinasida bosim tushishi va quyosh nurlarining o'zgaruvchanligi ko'rilgan. Bo'shliqsimon nur qabul qilgichlar ichida metal quvurlar ishlatilishi yuqori haroratga erishishning ishonchli yechimlaridan biri hisoblanadi. Quvurli bo'shliqsimon nur qabul qilgichlarning issiqlik modeli tasvirlanib, bunda issiqlik almashinish, bosim tushishi va narxni optimallashtirish ko'rilgan. Shuningdek qabul qilgichning effektivligini baholashda issiqlik modellashtirishning aniq bo'lishi muhimligi urg'ulanadi. Natijalar shuni ko'rsatadiki kattaroq o'lchamli nur qabul qilgichlar kattaroq effektivlikka ega, ayniqsa qisman yuklama holatida. Bundan tashqari natijalar, energiya ta'minotining barqarorligini ta'minlash maqsadida quyosh-gaz turbina qurilamarini rivojlantirishni ko'zda tutadi.

Kalit so'zlar: *kombinatsiyalashgan siklli stansiya, gaz turbina, quyosh nuri qabul qilgich,harakatlanuvchi oynalar, issiqlik almashinish, metal quvurlar, issiqlik modeli,*

nur qabul qilgich effektivligi, bosim tushishi, narxni optimallashtirish, quyosh minora tizimi.

Этот статья исследует интеграцию солнечной энергии в газовые турбины электростанций с комбинированным циклом (ГТУ с КЦ) с использованием солнечного приемника для нагрева воздуха, выходящего из компрессора, перед его поступлением в камеру сгорания газовой турбины. Концепция включает в себя концентрацию и направление солнечного излучения на приемник с помощью подвижных зеркал, что приводит к высоким температурам, необходимым для эффективной генерации энергии. Преимущества этого подхода по сравнению с другими концепциями солнечных электростанций выделяются. В статье также рассматриваются проектирование и вызовы приемника, особенно в системах газовых турбин, включая ограниченное падение давления и неравномерное распределение теплового потока. Использование металлических труб в полостных приемниках является многообещающим решением для достижения высоких температур и тепловых мощностей. Описано тепловое моделирование трубчатых полостных приемников с учетом теплообмена, падения давления и оптимизации стоимости. Подчеркивается важность точного теплового моделирования при оценке эффективности приемника. Результаты показывают, что более крупные конструкции приемников достигают более высокой эффективности, особенно при частичной нагрузке. Полученные выводы способствуют пониманию и развитию солнечно-гибридных газовых турбинных систем, предлагая устойчивый и привлекательный вариант для энергетической инженерии.

Ключевые слова: *электростанции комбинированного цикла, газовые турбины, солнечный приемник, высокие температуры, подвижные зеркала, теплообмен, приемник, металлические трубы, термическое моделирование, эффективность приемника, падение давления, оптимизация затрат, солнечная турбинная система.*

This article explores the integration of solar energy into gas turbines of combined cycle power plants (CCPP) by utilizing a solar receiver to heat the compressor discharge air before it enters the gas turbine combustor. The concept involves concentrating and directing solar radiation onto a receiver using movable mirrors, resulting in high temperatures required for efficient power generation. The advantages of this approach over other solar power plant concepts are highlighted. The article also discusses the design considerations and challenges of the receiver, particularly in gas turbine systems, including limited pressure drop and inhomogeneous heat flux distribution. The use of metallic tubes in cavity receivers is a promising solution to achieve high temperatures and thermal powers. The thermal modelling of tubular cavity receivers is described, considering heat transfer, pressure drop, and cost optimization. The importance of accurate thermal modelling in evaluating receiver efficiency is emphasized. Results indicate that larger receiver designs achieve higher efficiency, especially under partial load conditions. The findings contribute to the understanding and developing of solar-hybrid gas turbine systems, offering a sustainable and attractive option for energy engineering.

Keywords: *combined cycle power plants, gas turbines, solar receiver, high temperatures, movable mirrors, heat transfer, receiver, metallic tubes, thermal modelling, receiver efficiency, pressure drop, cost optimization, solar tower system.*

1. Introduction

The current trends in energy supply and use are evidently unsustainable in terms of their economic, environmental, and social implications. Without decisive action, it is projected that energy-related CO_2 emissions will more than double by 2050, and the increasing demand for oil will heighten concerns regarding supply security [1].

In light of these challenges, one potential solution lies in the hybridization of gas turbines. By integrating renewable energy sources, such as solar power, with gas turbine systems, the overall efficiency and environmental performance can be

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improved. This approach offers a promising avenue for addressing the pressing issues associated with the current energy landscape.

Solar energy can be introduced into gas turbines of solar-hybrid combined cycles (SHCC) through various methods. However, introducing solar power through heating the compressor discharge air using solar energy before it enters the gas turbine combustor offers distinct benefits over other solar power plant concepts. This method requires a high concentration of solar radiation to achieve the required high temperatures. A solar receiver is a promising way to achieve this [2]. In a solar receiver, a large number of movable mirrors, also known as "heliostats," concentrate and aim the incoming solar radiation at a receiver that is located on top of a tower. The receiver's primary function is to transfer the energy contained in the highly concentrated radiation to the heat transfer medium, which is pressurized air [3]. A scheme of the concept is shown in Figure 1. The solar-hybrid gas turbine approach is beneficial for various reasons, including the fact that it provides distinct advantages over other solar power plant ideas. The utilization of solar energy in the gas turbine of an SHCC can be accomplished by heating the compressor discharge air using solar energy before it enters the gas turbine combustor [4]. To achieve the necessary high temperatures, a high concentration of solar radiation is required, which can be accomplished through a solar receiver. The plant utilizes a large number of movable mirrors to concentrate and direct the incoming solar radiation onto a receiver, which transfers the energy to the pressurized air heat transfer medium [5]. Overall, the introduction of solar energy into gas turbines of SHCC offers significant advantages over other solar power plant concepts, making it an attractive option for energy engineering.

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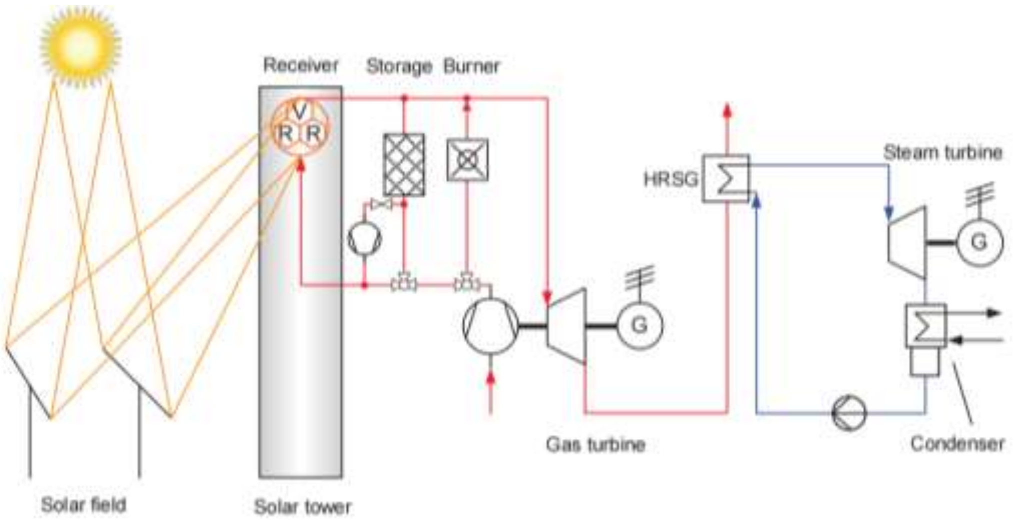

Figure 1. Solar-hybrid Combined Cycle (SHCC)

The receiver is a crucial component in a solar tower system, as it is responsible for capturing and transferring highly concentrated solar radiation into usable energy. In gas turbine systems that use air as the heat transfer fluid, the receiver design must account for the limited pressure drop of the gas turbine, which can cause low heat transfer rates. Additionally, high operating temperatures combined with inhomogeneous heat flux distribution on the receiver can be obstacles to achieving high receiver efficiency. To address these challenges, receivers are commonly located in a cavity where heat losses are reduced by lowering the heat flux, resulting in lower temperatures on the absorber [6]. This approach is beneficial for gas turbine systems, as the internal reflections inside the cavity lower the optical and infra-red radiating losses. One common method of constructing such a receiver is the use of metallic tubes [7]. The SOLGATE project developed a tubular receiver that heats up air from 290°C to 500°C with a thermal power of 300 kW. Similarly, the SOLHYCO project developed a tubular receiver for a micro turbine system that heats up air from 600°C to 800°C with a thermal power of 300 kW. In the SOLUGAS project, a tubular receiver was developed that heats up air from 330°C to 800°C with a thermal power of 3 MW. The development of efficient receivers is critical for the success of solar tower systems, particularly in gas turbine applications. The use of metallic tubes in cavity receivers has shown promise in achieving the necessary high temperatures and thermal powers required for these systems [8].

2. Thermal modelling of a tubular cavity receiver

The efficient transfer of solar radiation into heat energy is an essential component of solar tower systems. In such systems, the receiver plays a crucial role in capturing and utilizing the sun's energy to generate power. Specifically, in gas turbine systems, where air serves as the heat transfer fluid, the design of the receiver must address challenges such as low heat transfer rates due to the limited pressure drop of the gas turbine, high operating temperatures, and inhomogeneous heat flux distribution on the receiver. To overcome these challenges, the receiver is commonly located in a cavity, which reduces heat losses by lowering the heat flux and results in lower temperatures on the absorber. Additionally, internal reflections within the cavity reduce optical and infra-red radiating losses. A common way to construct such a receiver is by using metallic tubes, which are arranged between headers that form rings to distribute and collect the inlet air. The presented receiver designs are designed to heat up compressed air from 330°C up to 800°C with a mass flow of 15.9 kg/s at 10 bars and a maximum pressure drop of 250 bars. The absorber tubes absorb solar radiation, and the outer diameter of the cavity depends on the number of tubes and the thickness of the inner insulation. The allowable pressure drop of the turbine limits the possible mass flow within the absorber tubes, as pressure drop is strongly related to fluid velocity. The required number of parallel connected absorber tubes is given by the inner diameter and the length of the tubes [9]. From a thermodynamic point of view, small diameters and short tubes would be ideal as they maximize the heat transfer ability. However, a high number of parallel tubes increases manufacturing costs and must also be considered. To filter possible receiver designs, an EXCEL/MATLAB based tool was used that considered manufacturing and material costs of the receiver as specific costs based on current prices of materials and costs for several manufacturing steps (drilling holes, welding tubes, assembling). The tool aims to find the ideal receiver

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configuration that fulfils thermodynamic needs at the lowest costs. The heat transfer from the absorber tubes into the working fluid is modelled by discretion the absorber tubes into a large number of segments along the flow direction resulting in a one-dimensional approximation [10]. Heat transfer into the fluid is calculated using Nusselt correlations found in at each discrete segment using temperature-dependent fluid properties. The pressure drop at each segment is calculated using Reynolds-correlations from. The wall thickness of the tubes and headers is determined by an empiric formula for pressure vessels found in and using material stresses for the given temperatures. Table 1 shows the results of two receiver designs with different receiver dimensions (V1-small receiver; V2-large receiver). Design V2 has higher specific costs than V1, mainly due to higher material costs (absorber tubes and cavity insulation). Figure 2 gives an impression of the overall dimensions of the two receiver designs.

Table 1

	Design results	Receiver V1	ReceiverV2
1	Number of parallel absorber tubes	200	270
2	Inner diameter absorber tube [m]	0.025	0.025
3	Outer diameter absorber tube [m]	0.03	0.03
4	Radiated length of the absorber tubes [m]	6	10
5	Cavity aperture area [m^2]	12.6	12.6
6	Internal cavity area [m^2]	206.2	420.1

7	External cavity area [m^2]	239.5	466.6
8	Average heat transfer coefficient [W/m^2 K]	465	370

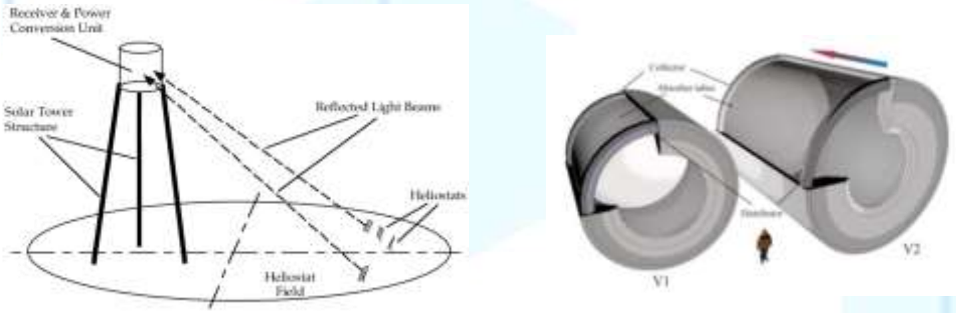

Figure 2. Receivers

Overall, the presented receiver designs aim to maximize the heat transfer from the absorber tubes into the working fluid while minimizing manufacturing and material costs. The results demonstrate that a smaller receiver configuration is more cost-effective, although larger configurations may be necessary to meet specific thermodynamic requirements. The use of EXCEL/MATLAB based tools allows for an efficient and effective evaluation of receiver designs, which is crucial in developing and optimizing solar tower systems for power generation.

Thermal model.

The efficiency of solar thermal receivers is an important aspect to consider when designing solar receivers. To evaluate the performance of these receivers, a thermal finite element (FE) model is commonly used. This type of model takes into account the complex interactions between various components of the receiver, including the absorber tubes, cavity walls, and ambient environment. The thermal FE model used in the evaluation of receiver efficiency considers the radiation exchange between the absorber tubes, cavity walls, and ambient using a ray-tracing-based algorithm for the solar wavelength. This algorithm is able to accurately calculate the expected heat flux distribution by taking into account both direct absorption and grey diffuse solar radiation exchange. The model uses the geometric data and optical properties of each FE of the mesh to perform these calculations. In order to model the absorber and cavity, the model assumes an absorptivity of 0.9 for the absorber and 0.3 for the cavity. The heat transfer to the working fluid is modelled using one-dimensional fluid-flow elements, which consider the heat and mass transfer of the fluid using temperature-dependent fluid properties and a heat transfer coefficient. At the infra-red wavelength, the radiation exchange is modelled using the grandiosity method of the FE code. This method calculates the energy exchange between surfaces by considering their radiative properties, including their emissivity and view factors. The model also takes into account heat losses by convection to ambient, which is estimated using a Nusselt correlation at the inner area of the cavity. This allows for accurate modelling of heat transfer between the absorber and the working fluid [10].

The conduction losses through the insulated cavity are modelled as a heat flow at the outside walls of the cavity. This allows for accurate modelling of heat transfer between the cavity and the surrounding environment. The thermal FE model used in the evaluation of receiver efficiency is a complex and sophisticated model that takes into account a wide range of factors that affect the performance of solar thermal receivers. By accurately modelling the interactions between the various components of the receiver, this model can provide valuable insights into the efficiency of solar thermal power plants and help to improve their design.

Results.

The thermal model's results are presented in Table 2. At the design point, the smaller receiver, referred to as V1, achieved an efficiency of 75%, while the larger receiver, V2, achieved an efficiency of 80%. It is worth noting that the efficiency of the V1 design is lower than that of the V2 design, due to the higher material temperature resulting from the higher heat fluxes inside the cavity. This increase in temperature

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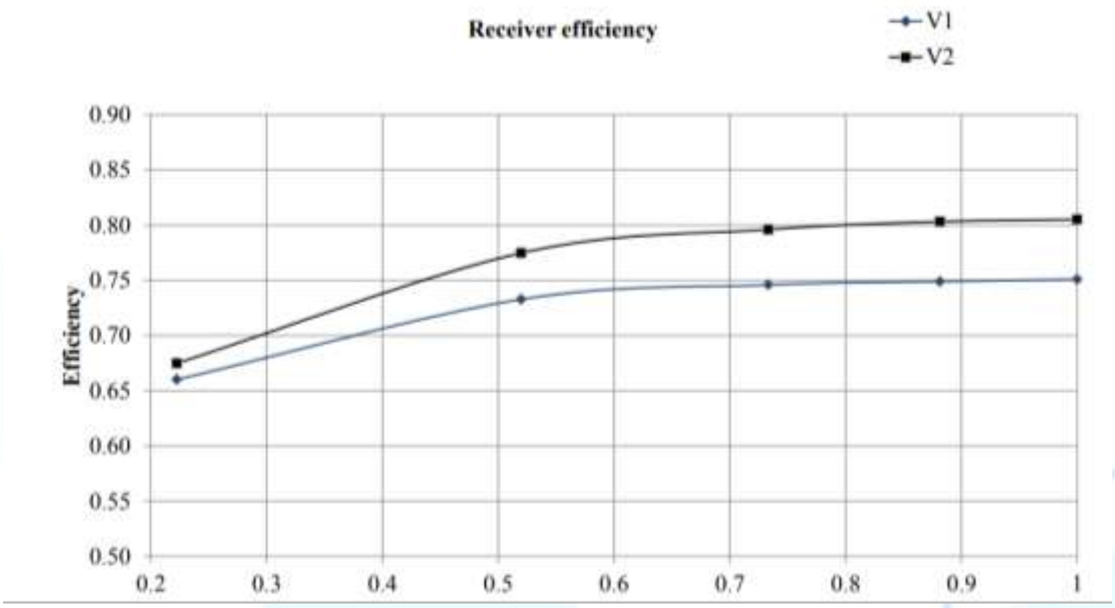
leads to higher radiation and convection losses, thereby decreasing the efficiency of the V1 design. Additionally, the V1 design's optical losses are higher than those of the V2 design, since the cavity effect is smaller in V1 than in V2. However, the conduction losses do not significantly contribute to the efficiency difference between the two designs.

Moreover, it is observed that the receiver efficiency is lower during part load situations, as shown in Figure 3. This may be attributed to the decrease in the incident solar radiation on the receiver. Consequently, the heat flux inside the cavity decreases, causing a reduction in the thermal performance of the receiver. These results suggest that the larger receiver design (V2) is more efficient than the smaller one (V1) and may be a better choice for practical applications, especially under partial load conditions.

Table 2

		Receiver V1	Receiver V2
1	Receiver optical efficiency	0.94	0.97
2	Receiver thermal efficiency	0.80	0.83
3	Receiver total efficiency	0.75	0.80
4	Maximum absorber temperature [°C]	1030	895
5	Maximum cavity temperature [°C]	1190	1013



In summary, solar energy can be introduced into gas turbines of solar-hybrid combined cycles (SHCC) through various methods, and heating the compressor discharge air using solar energy before it enters the gas turbine combustor offers distinct benefits. This method requires a high concentration of solar radiation, which can be achieved through a solar receiver. The receiver is a crucial component in a solar tower system, and tubular receivers using metallic tubes have shown promise in achieving high receiver efficiency. The presented receiver designs are designed to heat up compressed air from 330°C up to 800°C with a mass flow of 15.9 kg/s at 10 bars and a maximum pressure drop of 250 bars. To filter possible receiver designs, an EXCEL/MATLAB based tool was used to find the ideal receiver configuration that fulfils thermodynamic needs at the lowest costs. The heat transfer from the absorber tubes into the working fluid is modelled by the discretion of the absorber tubes into a large number of segments along the flow direction resulting in a one-dimensional approximation. Heat transfer into the fluid is calculated using Nusselt correlations found in each discrete segment using temperature-dependent fluid properties. The pressure drop at each segment is calculated using the Reynolds-correlations form. The wall thickness of the tubes and headers is determined by an empiric formula for pressure vessels found in and using material stresses for the given temperatures [10].

Reynolds-correlations

Reynolds-correlations refer to a set of equations that are used to calculate the friction factor and pressure drop in fluid flow through pipes or tubes. These correlations were developed by Osborne Reynolds and are based on experimental data. The friction factor is a dimensionless quantity that describes the resistance to fluid flow in a pipe or tube and is typically represented by the symbol f. The Reynolds number, which is also a dimensionless quantity, is used to determine the regime of fluid flow, whether it is laminar or turbulent. Reynolds correlations are used in the modelling and simulation of fluid flow to predict the pressure drop and flow rates in a given system. There are several Reynolds-correlations available, including the Colebrook-White equation and the Haaland equation, among others. The Reynolds number is defined as:

$$Re = \rho u \, {}^{D}\!/_{\mu}. \quad (1)$$

Nusselt correlation

The Nusselt number is a dimensionless number used in the study of convective heat transfer. It relates the convective heat transfer coefficient to the thermal conductivity and the characteristic length scale of the system. The Nusselt number is defined as:

$$NuL = \frac{Convective\ heat\ transfer}{Conductive\ heat\ transfer} = \frac{h}{{}^{k}\!/_{L}} = \frac{hL}{k}. \quad (2)$$

Gnielinski correlations

The Gilinsky correlations are used to calculate the friction factor and Nusselt number in turbulent flow heat transfer. These correlations are an extension of the Dittus-Boelter correlation, which is only valid for smooth pipes and laminar flow.

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The Nusselt number correlation is given by:

$$Nu_{Dh} = \frac{\left(\frac{f}{8}\right)(Re_{Dh}-1000)Pr}{1+12.7(f/8)^{\frac{1}{2}}(Pr^{\frac{2}{3}}-1)}; \quad (3)$$

where:

Dh is the hydraulic diameter [m].

Re is the Reynolds number [-].

Pr is the Prandtl number [-].

Nu is the Nusselt number [-].

f is the Darcy friction factor [-].

These correlations are widely used in engineering applications for turbulent flow heat transfer, and they have been shown to be accurate for a wide range of pipe diameters, flow rates, and heat transfer fluids.

Thermal Finite Element (FE) model

The thermal Finite Element (FE) model is a computational approach used to simulate and analyse the thermal behaviour of a physical system or component. It is based on the finite element method, which involves dividing the system or component into small, interconnected elements, and then solving a set of mathematical equations to calculate the temperature distribution within each element.

In a thermal FE model, the geometry and material properties of the system or component are defined, and boundary conditions are applied to simulate the thermal loads and thermal environment. The heat transfer equations are then discretized and solved numerically for each element, taking into account the effects of conduction, convection, and radiation.

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The output of a thermal FE model typically includes temperature distributions, heat fluxes, and thermal gradients within the system or component, as well as other thermal performance metrics such as thermal stress, deformation, and fatigue life. This information can be used to optimize the design of the system or component, evaluate its thermal performance under different operating conditions, and predict its durability and reliability.

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