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Solar dish and thermal energy storage for pre-heating in combustion processes

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Abstract

The global pursuit to integrate renewable energy systems with industrial and domestic applications to reduce reliance on fossil fuels renders concentrated solar power solutions attractive. A solar dish has been designed and constructed for integration with a small-scale air Brayton cycle (recuperated) at the University of Pretoria; however, the solar dish has not yet been experimentally investigated for other direct heating applications. The current solution (cogeneration and hybrid cycle) has been designed to produce electric power using liquid petroleum gas that compensates, via combustion, for the solar irradiation variabilities. The current work focuses on the experimental investigation of the system's solar receiver integrated with a thermal energy storage unit and its performance for air preheating in combustion applications (unrecuperated). This enables the full characterization of the system's thermal efficiency as a function of solar irradiation. The solar dish setup uses air as the heat transfer medium extracting solar heat from the receiver and transferring it to a small-scale thermal energy storage module using solar salts for latent heat storage. This ensures stable temperature throughput despite solar variabilities. This paper shows the results that were found after initial testing.

Keywords: Concentrated solar power, thermal efficiency, solar energy, thermal energy storage.

1. Introduction

The fundamental source of energy on earth is the sun (Ali et al., 2021). The available energy from the sun that reaches the surface of the earth is enough to meet the annual power consumption demands of the world's population for as long as the sun exists (Denholm et al., 2010). The sun is an attractive source of renewable energy in regions with rich solar irradiation resources such as South Africa. If the energy from the sun can be optimally captured, stored, and used, problems involving energy demand and supply could be solved. These problems include the environmental issues caused by the burning of fossil fuels for power production.

As it stands, fossil fuels contribute to more than 85 % of the consumable energy worldwide in the form of coal, oil, and natural gas (Yakah, 2012). When fossil/hydrocarbon fuels are used for energy production, combustion is the conventional method used to extract energy in the form of heat. These sources are deemed unsustainable and are identified as major contributors to some health issues (Gasparotto and Da Boit Martinello, 2021, Stefanovic et al., 2018). In addition, the cost of their consumption is considered high (Bekhrad et al., 2020, Kumar et al., 2019).

This paper investigates the integration of solar heat energy in conventional combustion-heating methods, to reduce fossil fuel consumption. The combustion process is a non-reversible rapid chemical process involving the reaction of fuel with oxygen (available in the air). Products of this reaction include carbon dioxide, water, and several other harmful products. Figure 1 shows a schematic diagram of the combustion process as typically found in modern applications.

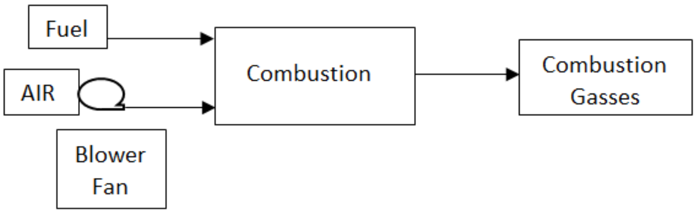

Figure 1: A typical combustion process

The products of this reaction are released at elevated temperatures as the reaction results in heat production. Heat is fundamentally the product of interest when the combustion process is used. The combustion process used in this work will not conform to any specific combustion procedure, however, a theoretical approach is used to set up the frame of work for the initial testing of an experimental setup.

Preheating air before combustion is an attractive method that improves the overall thermal efficiency of power cycles (Zachl et al., 2022). Preheating of air or fuel before combustion improved energy savings by 25%, pollution reduction by 50% and resulted in magnificent energy savings (Weber et al., 2020, Almutairi et al., 2022, Sue and Chuang, 2004). Weber et al. further stipulate that the dimensions of the combustion chamber can be optimized in some cases as a benefit of air preheating. Heated air can also be used in several industrial applications (Stefanovic et al., 2018).

To reduce the dependency on fossil fuel combustion, a solar dish system has been designed and constructed at the University of Pretoria. The design was focused on a recuperated Brayton cycle for electricity and heat generation where the combustion chamber was mounted between the receiver and the turbine. In this paper, the performance of the existing solar dish and receiver is evaluated for the pre-heating of air (unrecuperated). The paper reports on the initial prototype testing results aimed at the implementation of this method for combustion preheating.

2. Research Methodology

The total power input to the system is provided by the solar dish, and the available solar power is calculated using equation 1 below (Villarini et al., 2019):

$$\dot{Q}_s = A_d \times DNI \times \eta_s \tag{1}$$

Where $\dot{Q}_s$ is the solar power received at the receiver, DNI is the direct normal irradiance of the sun, A_d is the total reflective area and η_s is the solar reflector's reflectivity.

The system losses are not calculated in this work, however, the overall efficiency can be calculated using the total concentrated solar power and the process fluid's rate of energy gain calculated using the energy balance in equation 2 below (Schmitz et al., 2017):

$$\dot{Q}_r = \dot{m}_{air} C_{p,air} \left(T_{r,out} - T_{r,in}\right) \tag{2}$$

Where $\dot{Q}_r$ is the heat input to the receiver, $\dot{m}_{air}$ is the mass flow rate of the process air, $C_{p,air}$ is the specific heat capacity of air, and $T_{r,out}$ and $T_{r,in}$ are the outlet and inlet process air temperatures at the receiver, respectively.

3. Experimental setup

The existing solar dish comprised a solar concentrator, with an open cavity receiver. The process piping made from stainless steel 316 was used for the hot piping side of the receiver as well as in the existing Thermal Energy Storage (TES) unit. The prototype was designed and constructed for two-axis solar tracking. Figure 2 below shows the schematic of the system layout and the relationship of connected subcomponents to the system.

The concentrating dish reflector had an effective diameter of about 7.2 m focusing the incoming light to the focal length of about 4.3 m where the 0.25 m x 0.25 m aperture of the receiver was located. The geometrical concentration factor of the dish to the receiver aperture was calculated as 396 (Roosendaal et al., 2021).

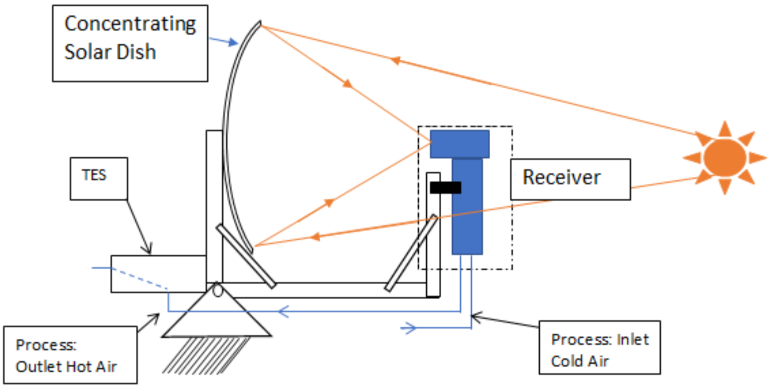

Figure 2: Schematic of the experimental setup (sun-rise position).

In the diagram below, the proposed solar-dish preheating process is shown with three solar preheating loops. Each path represents a direct preheating and combustion process. Mode 2 represents direct heating and charging of the thermal storage and mode 3 is the TES discharging process. In the initial experimental setup, the air leaving the TES is discharged into the environment. In Figure 3, the combustion chamber represents the same combustion chamber as in Figure 1 above, however, its functional parameters are not considered for this work, as they are not in any way altered for the subsequent process requirement. The combustion air inlet feeding from the solar dish prototype will be at an elevated temperature.

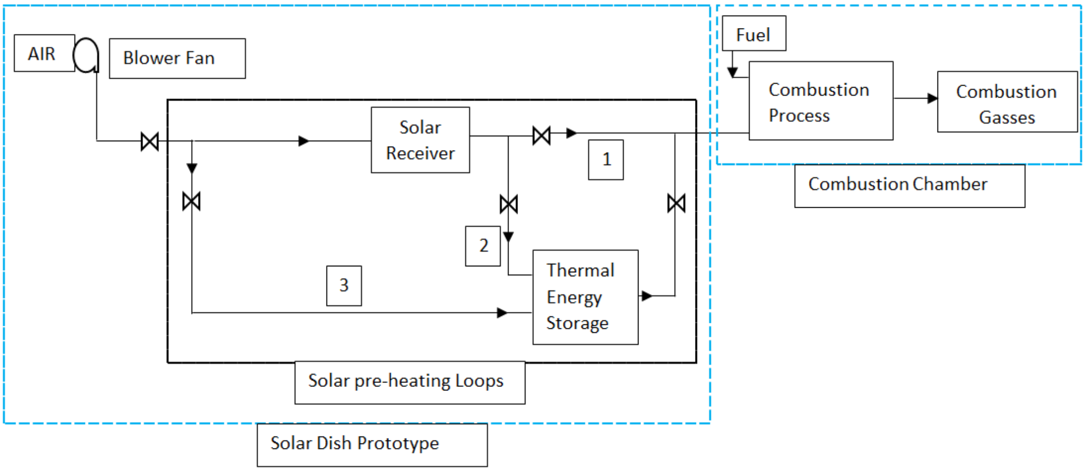

Figure 3 Process piping layout.

The solar dish sub-components are described in detail in the literature. The open cavity tubular receiver is used to absorb solar power for the process fluid (Craig et al., 2020, Le Roux et al., 2014). The existing solar dish was built from 46 facets manufactured using the methods described in the literature (Roosendaal et al., 2020, Roosendaal et al., 2021). New process piping was built from PVC piping on the cold side and stainless steel 316 (3 inches) on the hot side. K-type and T-type thermocouples and pressure sensors were installed along the process lines and around the system components. The experimental setup included the existing TES unit that enhances the availability of the system. The TES uses solar salts and it operates in both latent and sensible heat storage (Humbert et al., 2022). The application and benefits of thermal energy storage are discussed by Jose and Philip (Jose and Philip, 2016). The working fluid is introduced to the system using a Trim Tech 2800 W blower. The complete system setup in operation is shown below in Figure 4.

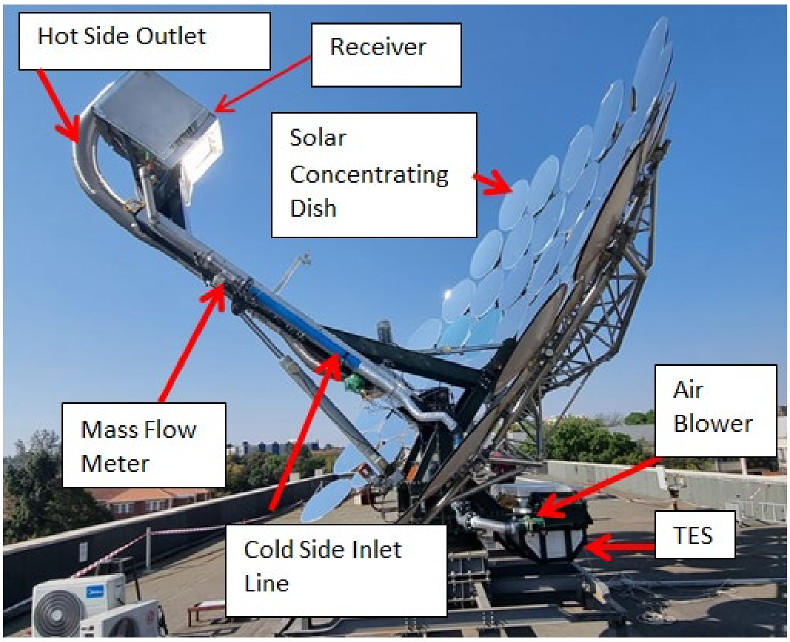

Figure 4 The completed solar-dish prototype for air pre-heating.

The experimental procedure started with the focusing of the dish facets onto the receiver. The manual focusing procedure takes place by manually positioning the facets to focus the reflected light onto the receiver, and also by applying vacuum pressure to the reflecting membranes (Roosendaal et al., 2021).

4. Results

The initial experimental testing was performed on the 29th of September 2022. The direct normal irradiation (DNI) data was available from the SAURAN station at the University of Pretoria (Brooks et al., 2015) situated about 120 m away from the prototype. Figure 5 shows the DNI data. Full system measurements started at 10:43. The facets were aimed from this time while the dish was continuously tracking the sun. The aiming procedure included manual alignment of the unfocused facets. During this time, the temperature of the receiver outlet was about 100 ℃. The facets were then focused onto the receiver using a vacuum pump. The focused light was directed at the focal point, with some facets still having spillage. When the facets were focused with the vacuum membrane technology, the temperature of the receiver outlet started to pick up (see Figure 6).

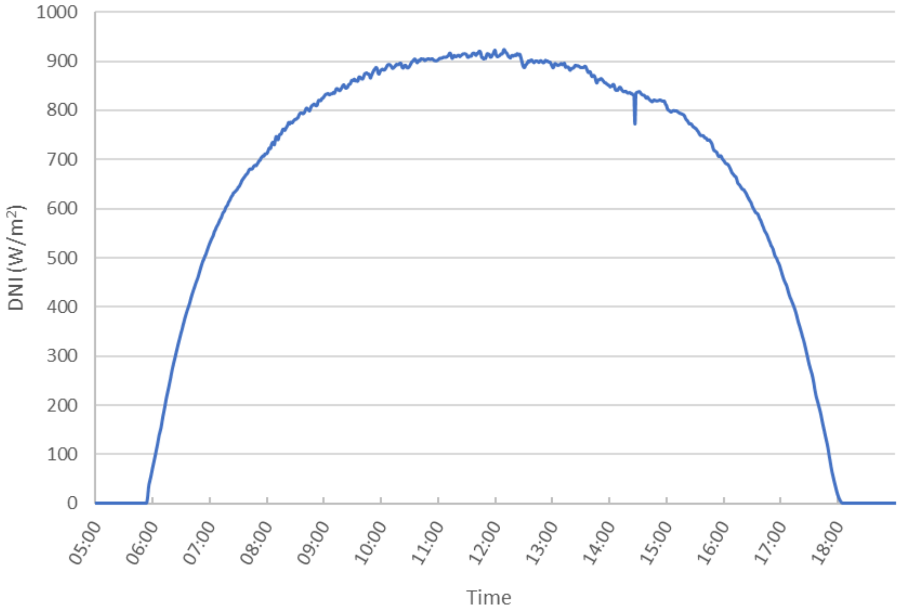

Figure 5: Direct normal irradiation on the day of experimental tests.

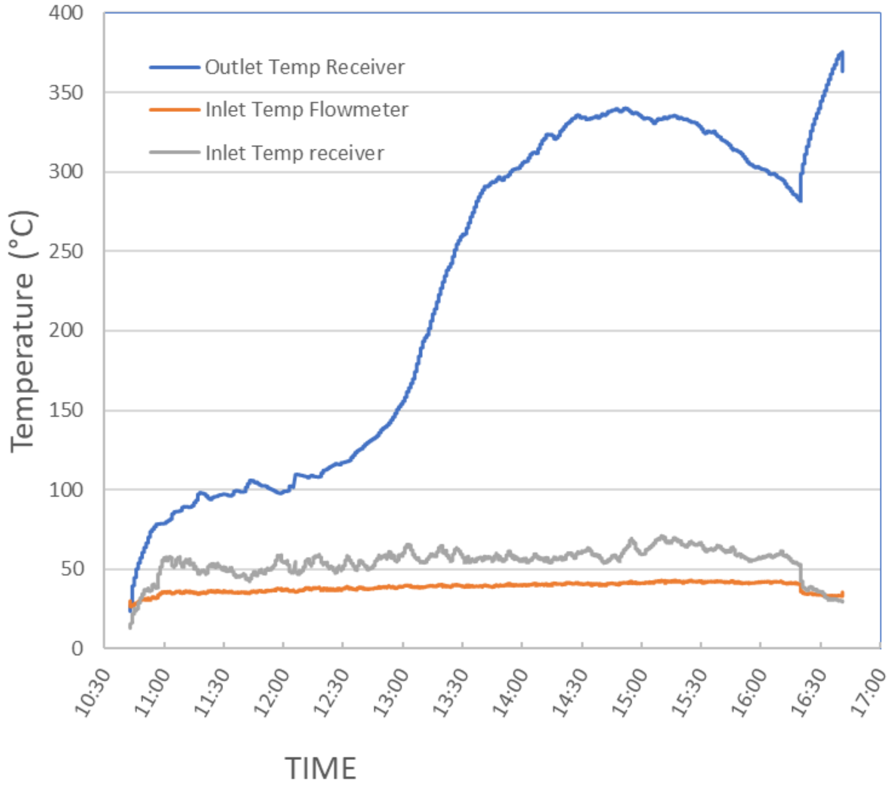

Figure 6: Temperature response of the system.

Figure 7 below shows the mass flow rate response as a function of time. As observed in Figure 6, the response shows that the increase in temperature of the system reduces the mass flow rate. Figure 8 shows how the overall efficiency of the system improved when the facets were focused on the solar receiver.

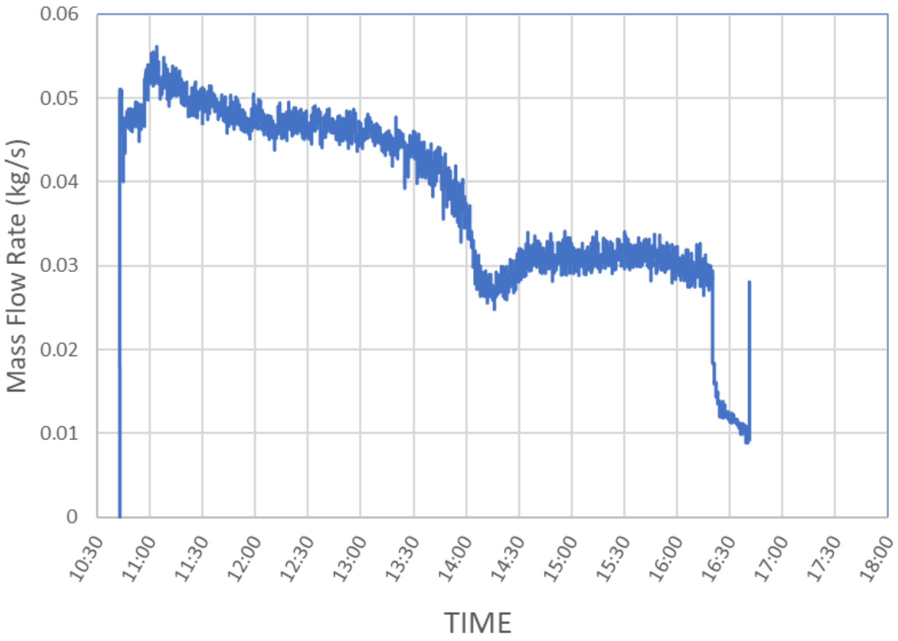

Figure 7: The measured mass flow rate during the test.

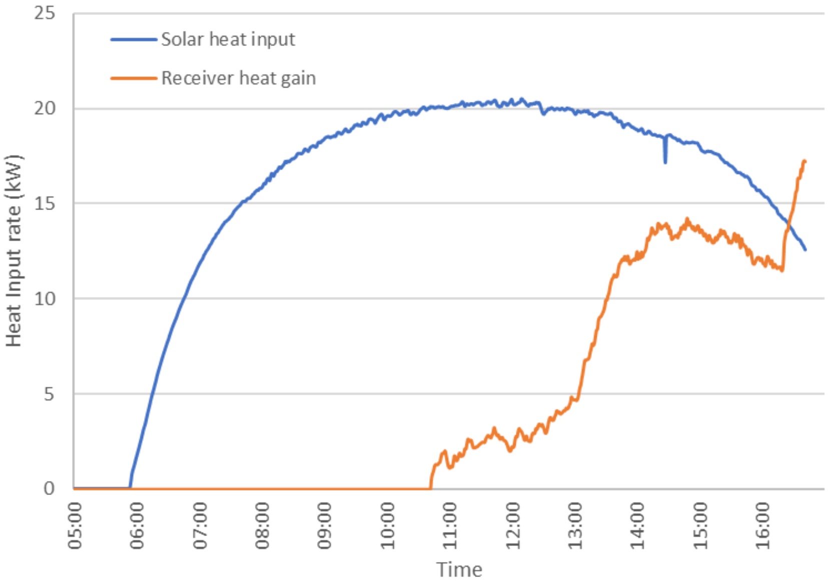

Figure 8: Captured solar heat and receiver captured solar heat during the test.

During the experiments at about 4:20 PM, the feeding line to the receiver developed a sudden major leak, and the experiments were stopped.

5. Conclusions and recommendations

The work reported in this paper is based on the results of the experimental work which was the first test of the prototype for preheating air for combustion processes. Future experimental tests will be carried out over an extended period. The current work does not include the investigation of solar spillage at the receiver. The connecting pipe to the TES suffered a thermal mass leak, and as a result, the results obtained from the TES were not analysed for this work. Furthermore, the cold side flexible hose suffered a major leak before the flow meter, and for future experimental testing and development, a different flexible hose must be used. The current experiments did not evaluate the pressure response for this system. In future, experimental tests will include the pressure response of the system. It is also recommended that the savings in terms of fuel be quantified to allow for comparisons. In practical applications, there will be the need to have a robust control system around the combustion chamber to manage all variables affecting the performance of the combustion chamber. Proper control will be required to ensure that the combustion chamber's outlet temperature is stable.

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