ANNULAR SOLAR RECEIVING TUBE

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Abstract

A receiver concept for an air standard Brayton cycle solar thermal power plant was tested experimentally. Test were conducted at low temperature and low pressure due to safety considerations and budget constraints. The receiver aims to mimic the greenhouse effect and comprise of an annular configuration, with a transparent outer tube and an opaque inner tube. A porous medium in the annular space serves to trap radiation and transfer heat to air flowing through it. Early test results were promising and the concept will be explored in depth in a master's study.

Keywords: Solar, Quartz tube, Annulus, Heat generation.

1. Introduction

SUNSPOT [1] is a solar driven system that generates electricity through a solar thermal system. The system is efficient and ideal for South Africa because of a high solar radiation flux, especially in the arid north-western part of the country [2]. The basic lay-out of the system is shown in Figure 1. The receiver is situated between the compressor and combustor. The heliostats concentrate radiation from the sun onto the central receiver where the heat is transferred to the air. The aim of the solar receiver is to increase the air temperature before it runs through the combustion chamber. Fuel is burned in the combustor if the receiver outlet temperature is too low.

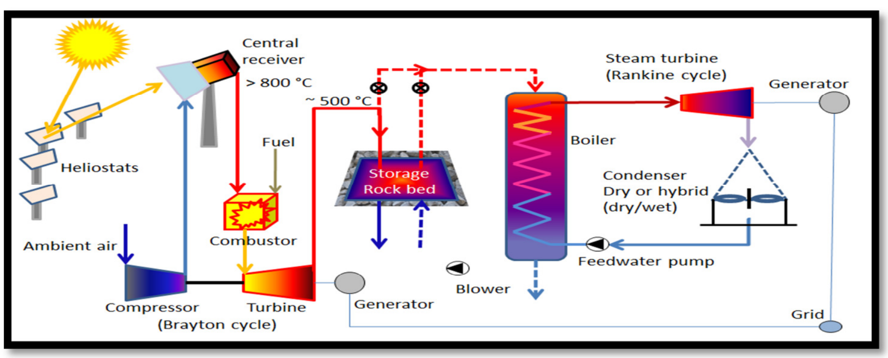

Figure 1: Representation of Basic SUNSPOT cycle [1]

According to Figure 2, it can be noted that the air is heated before it enters the gas turbine. This heating process increases the work output of the gas turbine at a specific air pressure. Air has poor heat transfer characteristics, which combined with the high heat fluxes associated with concentrated solar power, leads to material temperatures in the receiver substantially higher than the air temperature. Convection and radiation losses from the receiver at high temperatures can be significant and poses major challenges in the receiver design. Therefore the aim is to achieve a highest possible turbine inlet temperature at point 3 on Figure 2.

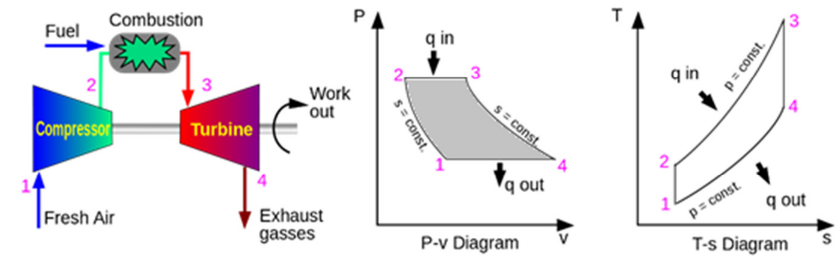

Figure 2: Representation of the ideal Brayton Cycle

The area inside the P-v diagram in Figure 2 represents the work output per unit mass flow rate of the Brayton cycle. The cycle efficiency could also be described in terms of the pressure ratio. When the efficiency is analysed in terms of the pressures it can be expressed as in equation 1. According to this relation the system must be operating at the highest possible pressure.

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{\frac{(k-1)}{k}}} \qquad \ldots (1)$$

with r_p the pressure ratio and k the specific heat ratio for air. Although a high pressure ratio is desirable for high efficiency, limiting the turbine inlet temperature may result in a turbine outlet temperature too low to sustain the bottoming Rankine cycle of the SUNSPOT cycle.

Open volumetric receivers, using a ceramic matrix were tested by Agrafiotis et al [3], whilst Carotenuto et al [4] used a metallic foam matrix. Although efficient, these receivers require compression of hot air. Álvira-Mariń [8] offers a comprehensive review of developments in open receivers up to 2009.

Jianfeng, Jing and Jianping [7] analysed the heat transfer and temperature distribution in an opaque tube irradiated from the side analytically. Their work is limited to forced convection on the inside of the tube, and a constant heat transfer coefficient.

Bertocchi, Karni and Kribus [5] suggested that radiation can be trapped in particle laden gas stream, but particles should be removed from the gas stream before they enter the turbine. Kribus et al [6] tested a multi-stage pressurized cavity receiver. Their pre-heater consists of a coil of metallic tubes and their "porcupine" receiver on the high temperature end. The "porcupine" is covered by a thick quartz window to maintain pressure and reduce radiation losses from the cavity.

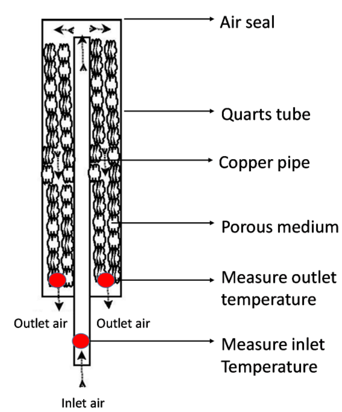

Figure 3: Representation of the air flow through the system

This research builds on the concepts suggested by various other researchers. An annular tube configuration is suggested, as shown in Figure 3. Air enters through the inner tube, turns through 180° at the top, and returns through the annulus. The outer quartz tube allows short-wave irradiation to penetrate and heat the opaque contents of the tube, whilst long-wave emitted re-radiation is trapped inside the tube, reducing radiation losses to the environment. The annular space is filled with a porous medium that absorbs solar radiation and at the same time offers a large surface area for heat transfer to the air. The irregular shape of the porous medium should ensure a high heat transfer coefficient, keeping the material temperatures in the porous medium low. Cold air enters through the inner metallic tube, keeping it cool and further ensuring structural integrity. Unequal thermal expansion of the two tubes and bowing under one-sided irradiation is taken up by the porous medium.

The problem is mathematically complex, with velocities, temperature and thermal radiation varying in the r, θ and z directions. The incoming radiation is approximately constant in the axial direction, but is expected to vary over the circumference of the tube. Furthermore, the thermal radiation is not aligned with the radial coordinate. As a result, no attempt was made to solve the problem mathematically.

Preliminary testing of the concept was done at low temperature and low pressure. The test rig, procedures and results that constitute the final year project of the lead author, are discussed in the following paragraphs.

2. Experimental setup

Final year projects typically run from February to October and testing usually starts during the winter recess and carry on until the spring break. Indoor and outdoor testing was considered during the initial design phase. Outdoor testing would use concentrated sunlight as energy source, whereas indoor tests would rely on an artificial light source.

Stellenbosch falls in a winter rainfall area, with cloudy weather dominating the months from June to August, putting outdoors testing at risk. Hence, the use of an artificial light source was preferred. A further benefit is that an artificial light source will provide a constant radiation intensity.

Tests were to be conducted at low temperature and low pressure. The aim of the project was to proof a concept, rather than a working prototype. The total temperature increase was limited to 10 °C which is at least an order of magnitude higher than any experimental uncertainty. Service air at 6 bar is available in the laboratory and the pressure was reduced to 0.5 bar using a pressure regulator. This air flow was kept constant during the entire test period.

Six 500 Watt halogen spotlights, at a distance of 600 mm from the tube, were used as light source. All attempts to measure the intensity of radiation failed and the radiation intensity at the tube was estimated from the electric power consumption of the lamps. The radiation emitted by a halogen lamp can be approximated as a grey body at 3 200 K [9], and the emissivity of the Tungsten filament is approximately 0.39 [10]. Glass will readily transmit all wavelengths up to 3 μm [11], but is essentially opaque for longer wavelengths. Hence, the intensity of the radiation emitted by the light source is found by integrating over all wavelengths below 3 μm, which is approximately 1 475 W/m^2. Neglecting reflection at the glass surface, the radiation intercepted by the tubes is approximately 110 W. At an air flow velocity of 5 m/s, this will cause an 11 °C temperature increase for the air.

Thermocouples for measuring air temperatures were not shielded from radiation. Assuming that the thermocouples are inserted in an irradiated part of the porous medium, they may record temperatures up to 0.3 °C higher than the air temperature for an estimated heat transfer coefficient of 200 W/m^2 °C [12]. This is rather conservative, as the thermocouples are inserted at the spacers, which shields them from radiation.

This system has the following limits that affect the maximum temperature: a minimum pressure of 500 Pa, a maximum length of 1.5 m and a maximum annular gap between the copper pipe and quartz tube of 17.5 mm. The flow was kept constant with the help of a FESTO flow meter. The flow rate was observed every 60 seconds to ensure that all the tests were done under the same conditions.

The minimum pressure is based on the performance of the pressure regulator. At pressures lower than 500 Pa, the pressure regulator can't maintain a constant flow rate. The length of the quartz tube was the determining factor for the length of the system. There was a limited availability of only two quartz tubes sizes, which gave a limit on the different nominal distances that could be tested.

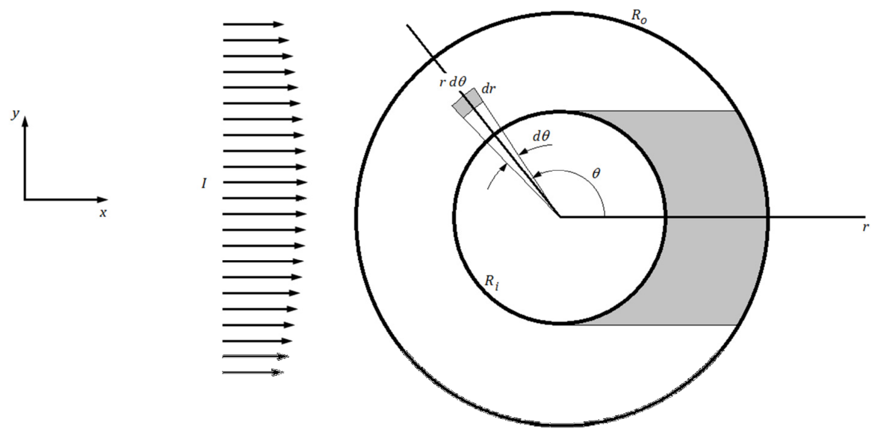

Figure 4: Attenuation of a radiation beam passing through porous medium.

According to Beer's law [10], the radiation flux through the porous medium will decrease exponentially. The rate of decrease is a function of the porosity of the medium. For low porosity values, the absorption coefficient is high, and radiation only penetrates a few millimetres into the medium. This phenomenon can be exploited by choosing the inner tube diameter such that $dI \to 0$ as $r \to R_i$. For a collimated beam in the positive *x*-direction, as shown in **Figure 4**, we have

$$dI = -\kappa dx = -\kappa[I_r dr + I_\theta r d\theta] = -\kappa I[\sin\theta dr + \cos\theta r d\theta] \quad \text{... (2)}$$

The incident radiation I is given by

$$I = \begin{cases} f(y) & for\, 90° \leq \theta \leq 270° \; for\, all\, r \\ f(y) & for -90° < \theta < 90° \; for\, r\sin\theta > R_i \\ 0 & for -90° < \theta < 90° \; for\, r\sin\theta < R_i \end{cases}$$

Where I_r and I_θ are the radial and circumferential components of I and κ is the absorption coefficient. Equation (2) assumes an isotropic absorption coefficient, and it does not take scattering into account. Since f(y) is unknown, equation (2) can't be solved analytically.

3. Test Conducted

Table 1 gives a summary of the different setups. The porosity (layers of porous medium) and the thickness of the porous medium (tube diameter) was varied in the test. . The radiation flux and volume flow rate were kept constant for all the tests.

The radiation flux was changed for a separate test by changing distance between the spotlights and the tube to examine the effect of the radiation flux on the system. In another test, the flow rate was changed to examine the effect of a higher inlet pressure.

Each test was conducted under constant conditions - the temperature of the room was measured before and after every test and the amount of energy contributed to the system, in the form of spotlights, was kept constant. The flow rate was also kept constant for each test.

Table 1: Different setups tested

Combination	50mm Tube	60mm Tube	Layers porous medium
1	X		3
2		X	3
3	X		4
4		X	4
5	X		5
6		X	5
7		X	6
8		X	7

The following parameters of the system were measured during the test: the flow rate of the inlet air and the average air temperature at the outlet. The tempo was only measured to ensure that the tests were conducted under the same conditions for each combination.

The temperature of each thermocouple was registered every 10 seconds by the data logger. These values were measured until the system had established a steady state. The average of the last 20 measurements was calculated in each case to compare the different combinations.

4. Results

The first set of tests was performed by changing the mass of the porous medium and the tube diameter and therefore the gap between the inner copper tube and the outer quartz tube. The results of the different combinations are surmised in Table 2.

Table 2: Results of different combinations tested

	Quartz tube diameter	
Layers of copper wool	***50 mm***	***60 mm***
3 layers	6.49 °C	7.20 °C
4 layers	7.87 °C	8.00 °C
5 layers	7.89°C	9.10 °C
6 layers		8.83 °C
7 layers		9.64 °C

The aim of the tests was to:

- Determine the effect of the different quartz tube diameters
- Testing different combinations to achieve a maximum temperature difference which the system can generate between the air at the inlet and the outlet as in Table 1.
- Determining the effect of different radiation concentrations

- Determining the effect of different volumes of copper wool

All of these aims were achieved during the tests and will be analysed separately below.

The system generated a maximum temperature difference of 9.64 °C as shown in Table 2 under combination 8. There is no specific aim set for the maximum temperature, because the tests were done under low pressures for safety reasons. The pressure needs to be high enough to limit any uncertainty in the temperature measurements. This uncertainty is, however, small and relative towards the temperature difference.

The increase in the temperature difference between the inlet and the outlet air was affected by increasing the gap between the quartz tube and the copper pipe. This correlation is shown in Section 4.

The reason for this phenomenon is that the total surface area allowing the light to enter through the 60mm tube is larger than the surface area of the 50mm tube. The volume flow rate is kept constant in all the cases. Another reason is that the convention heat transfer coefficient is dependent on the quartz tube diameter, as shown in Equation 4. This means more energy could be transferred to the air through a larger diameter.

$$q'_{21\_konv} = h_1 D_2 \pi (T_2 - T_1) \qquad \text{Eq. 4}$$

It is shown that a larger diameter quartz tube transfers more energy to the system at a lower radiation concentration.

As shown in Figure 5, the temperature difference increases as the volume of copper wool increases. It is shown in Table 2 that the 50mm tube achieves a constant temperature after the fifth layer of copper wool. This is the maximum volume of copper wool which can be used with regards to the nominal gap size. This phenomenon is also shown in the case of the 60mm tube.

This effect can be prescribed to the fact that the radiation does not penetrate through all the porous material, which results in a saturated porous medium.

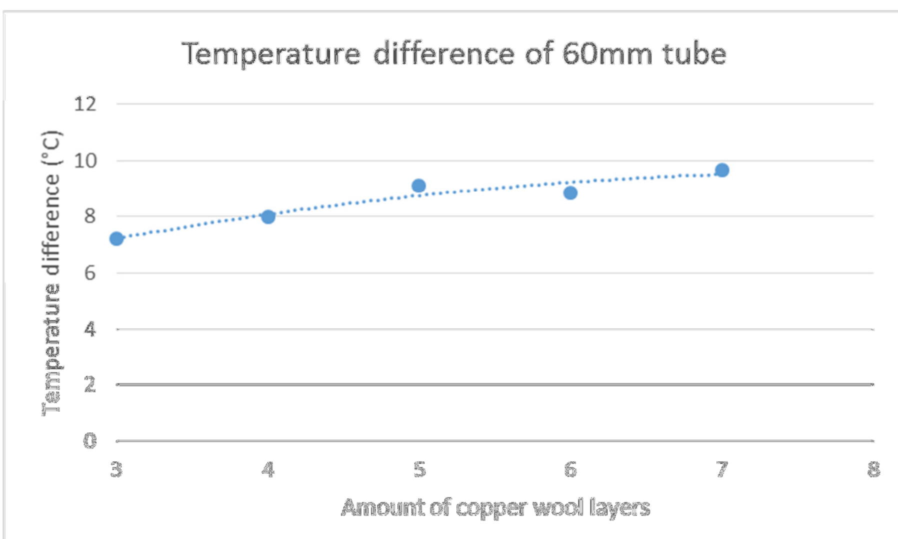

Figure 5: Increase in temperature with regards to the volume porous medium

5. Recommendations

The test program will be expanded in 2014 – 2015 to temperatures and pressures corresponding to those encountered in an actual solar receiver.

The size of the quartz tubes correlates with the amount of energy that can be transported to the air. The size of the quartz tube will also be limited by the hoop stress of the tubes, which will affect the amount of tension each tube can undergo before failure. This optimization problem must be analysed and solved in further studies.

A curved reflection mirror can be placed behind the quartz tube to increase the concentration of the light penetrating the quartz tube. This concept is better described as a parabolic through, where all the irradiation that is directed past the system is reflected back onto the system. This would result in a more uniform temperature distribution throughout the whole tube.

Packaging of the porous medium could be more constant when using another supplier of copper wool. Larger rolls are available in other countries. This would also increase the assembly time of the system.

Outdoor tests can be done where the radiation concentration is not constant. This data can be compared with the indoor tests to develop a relation between the simulated concept and the real concept. This simulated concept would imitate the simulation of the sun, with reference to the spotlights.

6. Conclusion

Preliminary test results at low pressure and temperature confirmed that the concept of an annular receiver is viable. These tests set a benchmark for future studies in the field. The receiver was capable of absorbing almost all incoming radiation. Of course, convective and radiation losses will be more significant at elevated temperatures.

The tests also show that the performance of the receiver depends on the porosity of the packing, as well as packing thickness, with the air outlet temperature increasing with an increase in both these parameters. On the down side, the pressure drop increased with an increase in the porosity. Careful optimization of the configuration is required, as tube diameter will be constrained by hoop stresses.

This study will be extended to intermediate (± 200 °C) to high (± 500 °C) temperatures, using concentrated sunlight rather than an artificial light source. At elevated temperatures a true assessment of convection and especially radiation losses can be made.

All these issues will be addressed in the Master's thesis of the lead author.

Acknowledgements

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