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The Design and Modification of a Parabolic Trough System for the Hydrothermal Liquefaction of Waste

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Abstract. We describe the design of a small-scale parabolic trough with a high-pressure absorber bundle to convert microalgae into bio-oil. The "proof-of-concept" system uses an existing Global CSP solar captor, with its reflectance enhanced by the addition of Skyfuel® ReflecTech Plus polymer film and has its original receiver tube replaced by a novel high-pressure multi-tube absorber and reactor. Initial results obtained at Kota University in Rajasthan, India demonstrated that temperatures up to 320˚C are possible, and a bio-oil, similar to palm oil, was extracted from the reactor.

INTRODUCTION

This paper details the design aspects and first results from a "proof of concept" demonstrator which combines the principles of Concentrating Solar Power (CSP) and hydrothermal liquefaction (HTL) for the treatment of waste feedstock to provide biofuel. HTL involves the conversion of biomass (including microalgae and cheaper waste feedstocks) to bio-liquid with bio-crude as the predominant by-product. This reaction occurs at temperatures of 280-370ºC and at pressures of 10-25MPa. We describe how concentrated solar heat and pressure can be used to drive this reaction.

An earlier study has highlighted the potential for HTL/CSP to provide sustainable microalgae bio-oil production using a parabolic trough (PT) with an adapted receiver tube system as the reactor [1,]. This was a theoretical study only. Practical work was carried out to verify whether the concept would be effective and indeed it was shown that it was, although the existing equipment at the time was not able to reach the required temperatures and pressures for the reaction to fully take place [2]. The study detailed here takes this work further, under the auspices of the "Solar Oil" project (an industrial and academic collaboration funded by Innovate UK). The work uses a small-scale PT from Global CSP which was adapted for the purpose by Cranfield University and tested at the University of Kota in India by the UK Company, Phycofeeds Ltd. Fig.1 below demonstrates the overall principle and Fig. 2 shows an original (un-adapted) solar captor from Global CSP, UK.

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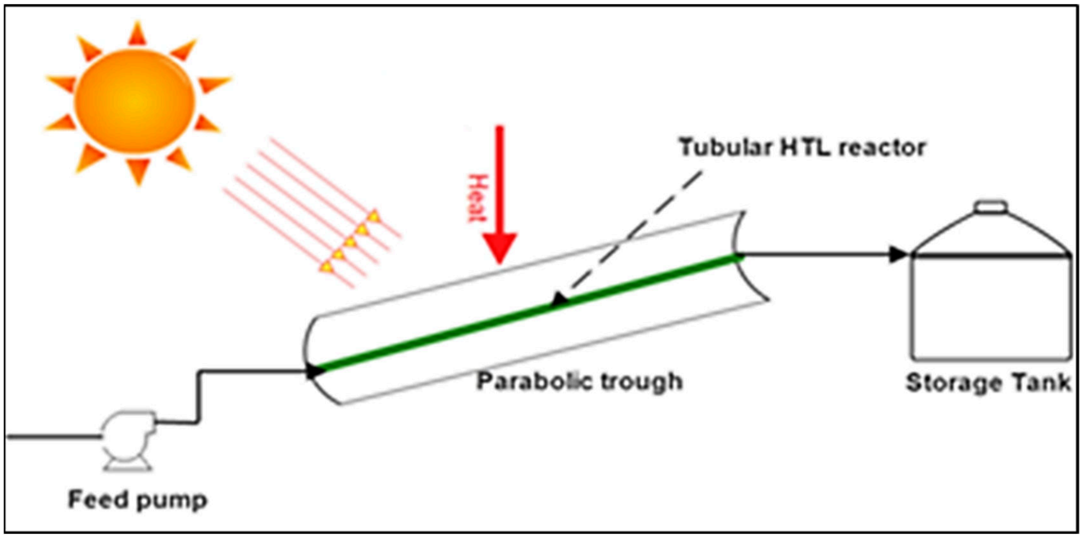

FIGURE 1. Combined CSP/HTL system concept [1]

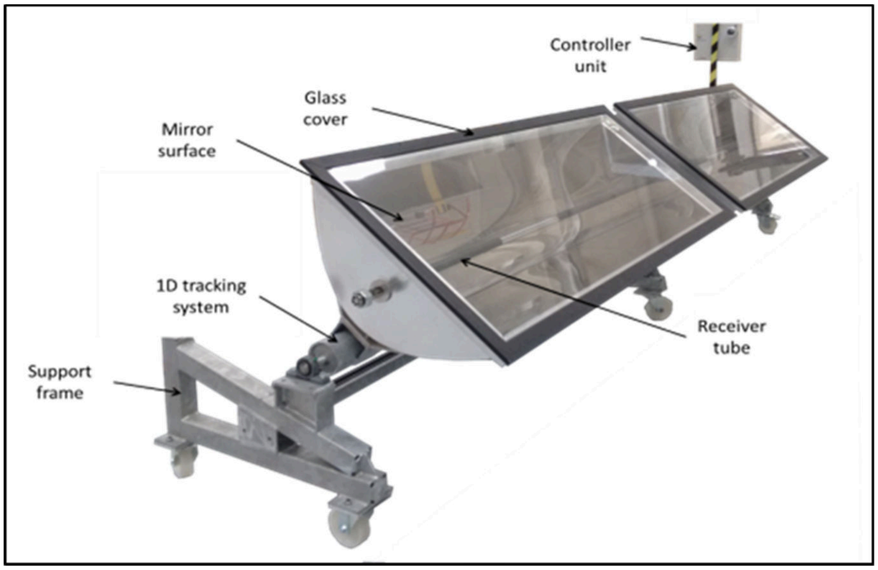

FIGURE 2. Captor (Global CSP, UK)

RECEIVER SYSTEM DESIGN

A PT type collector manufactured by Global CSP Ltd., UK (Fig. 2) was modified for the purposes of this study. This particular collector is aimed at small-scale CSP applications and is designed to achieve Heat Transfer Fluid (HTF) temperatures up to approximately 250˚C. The existing line-focus receiver consists of a 32 mm diameter black painted stainless-steel tube of 2 mm wall thickness, offset from the mirror at a focal distance of 120 mm. The system has overall dimensions of 690 x 1960 mm and is lidded to prevent the ingress of dust and to protect the reflecting polished metal surface and receiver. It has a manually controlled 1-axis tracking system.

Given the temperatures and pressures that the bio-reactor is expected to operate at, it was necessary to redesign the receiver system. This was rated to operate at 150-200 bar and 250-350˚C using Swagelok pipe and fittings.

The novel receiver design is composed of three main elements: a multi-pipe arrangement of black painted 8mm Swagelok® stainless steel tubes mounted inside an external 2m long borosilicate glass tube (Fig.3) and an aluminum secondary mirror. The stainless steel tubes were rated to withstand the temperature and pressures of the biomass conversion process. Different internal pipe configurations were tested (to limit shadowing effects and reduce temperature losses) and these were designed as a "bundle" to be more easily inserted or removed from the external tube. The various configurations had been previously tested using Ansys FEA software. The fitting of these entailed modifying the apertures for the existing absorber tube to take a larger diameter (50 or 55 mm OD according to which pipe bundle was being used), support bosses were manufactured from aluminium to support the tube. Wadding was used to seal the gaps at either end between the internal "bundle" and the external tube, to minimise thermal losses. In practice, four reactor tubes were used in a "rotated square" arrangement as this had proved to be the best compromise between reactor volume, limitation of shadowing effects and temperature losses and fitting within the given confines of the envelope tube. Pressure relief valves were also added to ensure safe working.

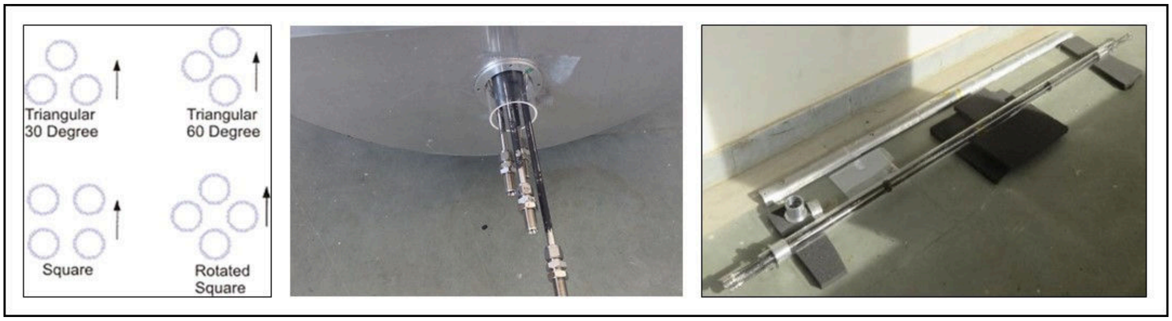

FIGURE 3. The modified receiver: multi-pipe stainless steel assembly within a glass envelope tube

SOLAR REFLECTOR SYSTEM RE-DESIGN

The original surface of the Global CSP parabolic reflector was constructed from polished stainless steel, and the unit was designed to achieve temperatures up to 250˚C. To improve the reflectivity and therefore achieve the appropriate temperature to initiate the conversion of the biomass, Skyfuel® ReflecTech Plus polymer film was applied in A4-sized strips along the length of the captor. This was difficult to retro-fit in practice and required much trial-and-error in order to achieve a smooth and uniform reflecting surface with a specular reflectance in excess of 90%. The A4-size strips of ReflecTech Plus are shown in place in the left-hand image of Fig.4 below.

The right-hand image of Fig.4 shows the installation of a secondary reflector, also added to enhance the optical performance of the captor in order to achieve the temperatures needed in the absorber tubes for the HTL reactions to occur. This secondary reflector is a 95% highly reflective aluminium construction, welded to a backing structure (also aluminium). This sits above the absorber tube, below the captor transparent lid, along the entire focal line. It is necessary only to compensate for the shape errors in the original parabolic trough and is a net benefit to performance despite its blocking of some incident solar radiation.

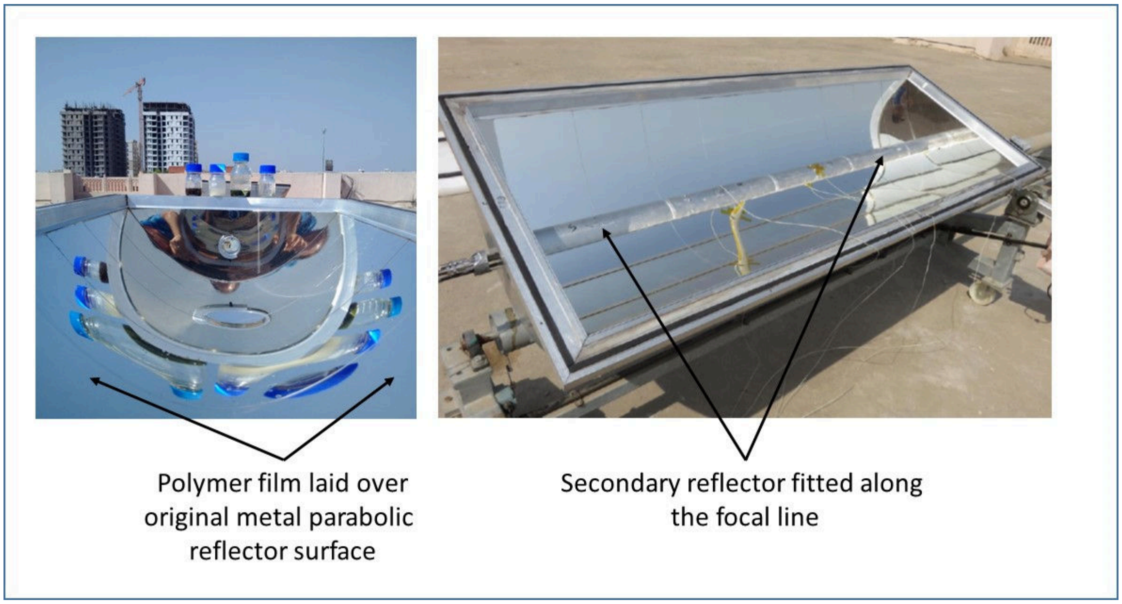

FIGURE 4. Strips of polymer film (Left) and the secondary reflector in place (Right)

RESULTS – MODIFIED DESIGN TESTING

The unmodified captor had previously been shown to achieve temperatures of 200-220°C at the chosen testing site at the University of Kota in Rajasthan in the north-west of India (see Fig 5. below). This was an encouraging result but deemed to be insufficient for the conversion process to occur successfully. However, in a pre-test of the modified design on a sunny winter's day at Cranfield University, UK (10-13°C ambient temperature), a temperature of 190-200°C was achieved at the receiver. This gave great hope for the ensuing installation and testing of the modified captor at the Kota site.

FIGURE 5. Testing location at Kota University showing DNI map [3] and images during installation

Kota has a DNI in excess of 2000 kWh/m^2/y as shown in the left-hand image of Fig.5 above. The center and right-hand images of Fig. 5 show scenes from the installation of the original captors on the roof of the engineering building at Kota University.

Installation and full testing of the captor took place in February-March 2018 when the ambient temperature was around 28-32°C. The captor was aligned North-South and initially manual tracking was used to track the sun's movement east to west. Temperatures in excess of 290°C were achieved during testing during February 2018 (with no fluid in the receiver pipes). Both heliostatic North-South and static West-East solar captor orientations achieved solar receiver average temperatures of between 220°C and 300°C from October 2017 to February 2018 and 320°C to

350°C from March to June 2018 using this CSP-HTL system. These peak temperatures are within the boundaries for HTL to occur (280°C to 350°C). The 4-pipe rotated-square profile of pipe bundle and glass external tube was in use at this time. Fig. 6 below shows the absorber pipe bundle in the right-hand image, with the microalgae and water mixture input pipes shown in the left-hand image.

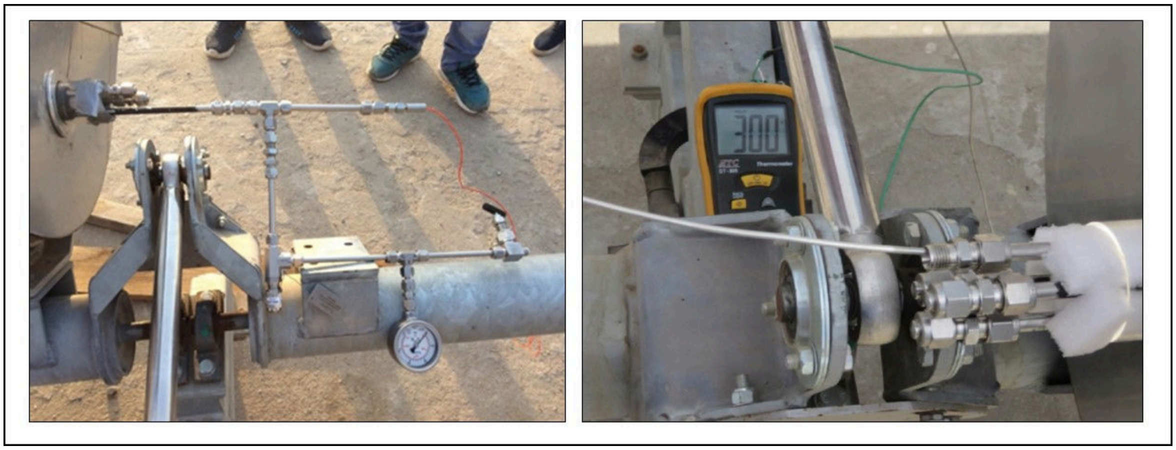

FIGURE 6. Testing location at Kota University showing biomass input pipe (left) and absorber bundle (right)

Note also in Fig. 6 that a temperature sensor reading is shown on a digital thermometer. The positioning of the temperature sensors and the extraction of meaningful readings for feedback purposes was a long and challenging activity. The positions of these sensors are shown in Fig. 7 below.

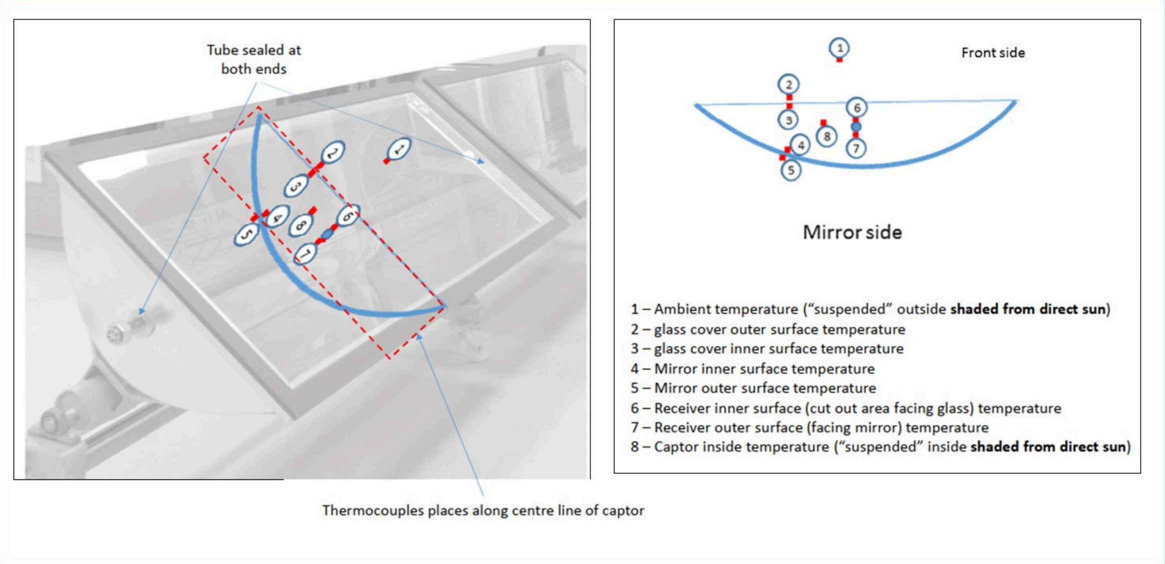

FIGURE 7. Testing location at Kota University showing biomass input pipe (left) and absorber bundle (right)

Eight thermocouples were added at specific positions along the length of the captor. These included PT100 type to measure the fluid temperatures within the stainless-steel pipes and K type to record temperatures on the reflective surface of the captor. These were positioned using high temperature tape.

Heliostatic tracking obtained a temperature increase of between 2°C to 15°C/min, depending on precision of control over solar tracking and variance from maximum temperature acquisition. There is therefore a trade-off in the extra capital expenditure needed for a heliostatic tracking system against the engineered optical design of the CSP collector-receiver.

The lid/cover of the captor proved to be somewhat challenging in that, the seal needed to be replaced upon its removal. Unfortunately, we were unable to use a high temperature glue at the time, so that a silicone-based sealant was used in its place. This led to considerable outgassing of the sealant in the Indian ambient temperatures and consequential steaming up of the cover lid which naturally entailed its removal and cleaning.

From a process demonstration point of view the experiments were deemed a success. The output of the solar process obtained during experimentation in March 2018 was a chemical mixture emulsion of hydrocarbons and organic compounds in water [4]. Gas Chromatography Mass Spectroscopy (GCMS) analysis was used to determine the composition of the oils and organic compounds in the blend. For example, PET (used to make drinking water bottles) after the solar process breaks down into mainly trans 1,4, Cyclohexanedimethanol with some 4, methyl Cyclohexanone and other compounds too. Likewise, Nannochloropsis microalgae produces a considerable quantity of hexadecanoic acid (the oil found in palm oil).

CONCLUSIONS

It has been shown that the design of a small-scale parabolic trough with a high-pressure absorber bundle can be used to convert microalgae into bio-oil. The “proof-of-concept” system uses an existing Global CSP solar captor, with its parabolic mirror reflectance enhanced by polymer film, the use of a secondary reflector, and with its original receiver tube replaced by a novel high-pressure multi-tube absorber and reactor. Initial results obtained at Kota University in Rajasthan, India demonstrated that temperatures up to 320˚C are possible, and a bio-oil similar to palm oil was extracted from the reactor.

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