Modelling an On-Sun Receiver/Reactor for Supercritical Water Gasification of Algae

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Solar-assisted thermochemical conversion of algae, and other farmed biomasses, into value-added liquid fuels such as diesel/gasoline or methanol, using supercritical water gasification (SCWG) offers a promising approach for "green" fuel production. SCWG has been shown to have lower char formation compared to conventional gasification and also has the ability to utilise wet biomass. Moreover, algae as a feedstock, can be grown in harsh environments (arid-land and salt water). In the case of expensive feedstocks, such as algae, providing the endothermic heat using concentrated solar thermal is important to improve the process efficiency and lower the fuel cost. In the Australian context, this technology is particularly attractive due to the co-location of solar, land and water resources in regions such as Pilbara (WA), Port Augusta (SA) and Geraldton (WA). Recently, SCWG technology has garnered significant attention on both lab-scale demonstration and system modelling aspects [1], however, the reactor design and optimisation are still relatively unexplored [2, 3]. Understanding the thermal- and tube-stresses in an on-sun receiver/reactor is important to identify the materials constraints. In this work, we extend our previous model [3], which assumed uniform flux distribution inside the receiver cavity, by implementing a polar heliostat field and using Monte-Carlo Ray Tracing (MCRT) for calculating realistic flux profiles on the receiver tubes.

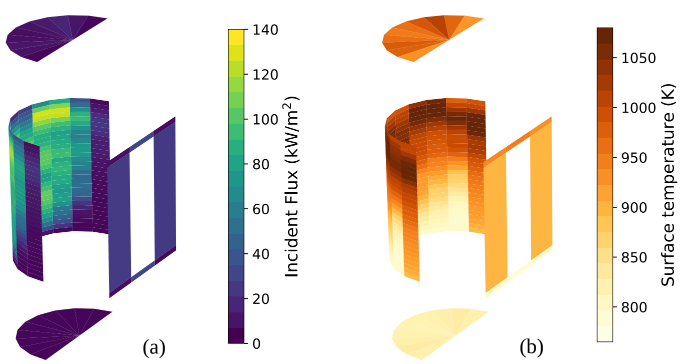

Figure 1: Cavity receiver, (a) Incident flux map accounting for reflections, and (b) Tube external-wall temperature under steady state

The design point for the heliostat field is 50 MW_{th} at equinox-noon for Geraldton (WA, Australia), with the layout optimised using SolarPILOT. The ray tracing was performed in two stages, one using SolTRACE [4] for generating the ray-data incident on a sphere/plane, and the other to re-sample and ray-trace the actual receiver geometry with Tracer [5]. A range of hemi-cylindrical cavity dimensions were evaluated to keep the peak flux below 130 kW/m^2. The hydrodynamic model consists of equilibrium prediction, mixture property calculation, and heat/mass transfer in the reactor. The model implements Peng–Robinson equation of state (PR-EoS) in conjunction with van der Waals (vdW) mixing rules and calculates the equilibrium composition through Gibbs free energy minimisation. The kinetics of algae gasification under a wide range of conditions were not available, hence, the decomposition was treated as zeroth order and char formation neglected. The reactor is assumed to be an arrangement of 8 vertical tube banks, each with 125 single-pass tubes in parallel. A pseudo steady state 1-d coupled model for radiosity and heat transfer is solved simultaneously with the equilibrium and transport models, assuming 400°C inlet temperature, 240 bar pressure and 15.16% algae concentration. The flow-rates in each tube bank were adjusted to achieve a fluid outlet temperature of 605°C. The equivalent von-Mises stress on each tube element was calculated based on the pressure and thermal stresses.

Fig. 1 shows the assumed cavity design, discretization and absorbed flux after accounting for cavity reflections. Fig. 1(b) shows the tube wall temperatures, where the maximum external tube wall temperature was ∼800°C. Figs. 2(a)–(c) show the product composition along the flow path for one representative tube, the fluid temperature, and the equivalent stresses in the reactor tubes. In Fig. 2(c), the equivalent stresses are represented for one tube in each bank and variation along the circumferential direction is shown. The thermal efficiency of the receiver/reactor, defined as the ratio of energy transferred into the fluid to that incident on the aperture, was ∼64%. The radiative and convective losses were each around 10–12% because of the large area of the aperture.

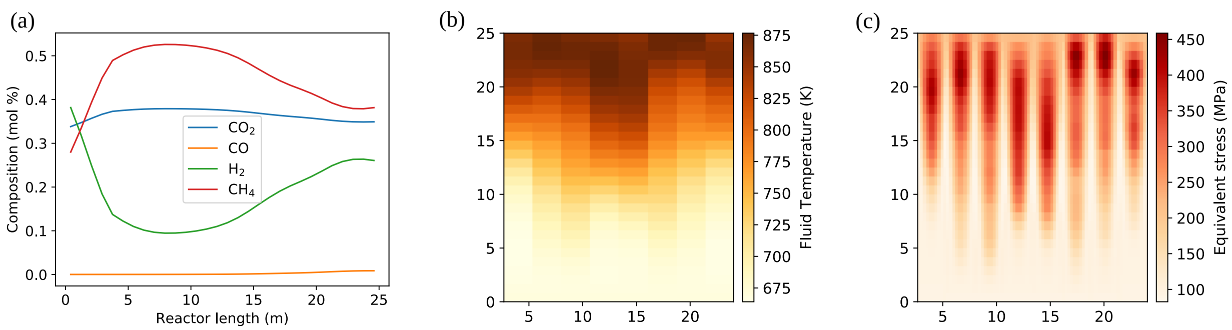

Figure 2: (a) Product composition along one representative fluid path, (b) Fluid temperature inside the tubes, (c) Equivalent stress on tube surface calculated based on von-Mises criterion. The x and y axes for subfigures (b) and (c) represent the position on receiver hemicylindrical face (distances in meters).

An on-sun SCWG receiver presents an interesting challenge; the high pressure stresses due to the process conditions warrant thick tubes, which in-turn increases the thermal stresses, and coupled with the low heat transfer capabilities of the supercritical fluid, leads to a low peak flux requirement. Even with a careful assessment of these factors, the peak equivalent stress was of the order of 450 MPa, which is beyond the capabilities of current metallic materials. Future work envisages optimisation of the cavity design and/or examining alternative system-level configurations that facilitate 360° heat transfer, for reducing the thermal stresses in the reactor tubes, and improving the energy/exergy efficiency of the on-sun SCWG reactor.

References

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