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PERFORMANCES OF HOLLOW CARBON SPHERES AS FLOATING BODIES FOR IMPROVED SOLAR EVAPORATION

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Introduction

Concentrating solar heat for boosting the evaporation of water, and thus producing pure water or steam from seawater for instance, attracts more and more interest. Efficient harvesting of solar energy for steam generation is a key factor for a broad range of applications, and hence solar evaporation processes with high efficiency are looked for. As an excellent photothermal material with high absorbance and low emittance, carbon installed at the surface of water should minimize heat losses and result in improved solar evaporation. In this context, the potential of floating hollow carbon spheres (HCSs) as solar steam generation enhancers is worth investigating. Combining the well-known chemical inertness of carbon at moderate temperature and its light-absorption properties, floating HCSs might indeed absorb sunlight and then convert it to thermal energy, resulting in an increase of the surface temperature of water and a significant enhancement of the water evaporation rate.

Materials and methods

Hollow carbon spheres (HCSs) were produced from sugar alcohols encapsulated in photocurable polymer shells. Two different diameters were tested, which were submitted to a hydrothermal treatment in aqueous solutions of carbon precursors. The latter were either sucrose or condensable tannin, and the treatment was performed in the presence or not of iron or nickel salts. Finally, pyrolysis was then carried out at either 900°C or 1500°C, leading to HCSs. Overall, 10 different kinds of HCSs were obtained because of the combination of different temperatures of pyrolysis, different carbon precursors, and different metals (or none) acting as graphitization catalysts.

These materials were thoroughly characterized by the following techniques: water contact angle, oxygen content, XRD, Raman spectroscopy, SEM-EDX. Their behavior in terms of water evaporation was also investigated by forming a floating monolayer in each of two identical beakers of diameter 2.8 cm containing 20 g of salt water. The concentration of NaCl was 3.5 wt.% for mimicking seawater. The two beakers were installed in a ventilated chamber with reflectors, as well as third identical one but free of floating HCSs and used as reference. A solar simulator placed at the top of the chamber allowed submitting the three beakers to radiant energy densities of 0.8, 1 or 1.3 kW/m^2, and the corresponding weight loss was continuously monitored as a function of time. Based on these experiments, the evaporation rate could be obtained for each kind of HCSs.

Next to this, the water evaporation was modelled based on several simplifying assumptions: (i) the absorbed radiation was considered as a source term proportional to the incident flux; (ii) the temperature of air and the water vapor pressure were considered constant in the chamber because of the continuous ventilation; (iii) the HCSs were assumed to be packed according to 2D square lattice. Based on the measured weight loss of water without HCS, the evaporation rate was calculated and then, HCSs were added to the system and the corresponding changes of evaporation rate were observed. The model was implemented with Comsol Multiphysics v5.2a with the “heat transfer” toolbox. A domain was considered in the form of a water column with a square section, whose side was equal to the diameter of a HCS, and with the HCS located at different heights in this column, from far below the surface up to a floating position above it, see Fig. 1.

Results and discussion

One kind of HCS enhanced the solar water evaporation by up to 70% under a radiant power density of 1.3 kW/m^2. The performances depended on diameter, precursor, presence of metal, and pyrolysis temperature. It was conjectured that an optimum exists between a too high hydrophobicity, making the HCSs float far above the waterline, and a too high hydrophilicity, making them sink, and that the balance between these limits is a complex combination of contributions from apparent density, oxygen content, graphitic character, and wettability of HCSs. However, all the aforementioned analyses failed at explaining in a self-consistent way the observed trend in the evaporation rates of the various kinds of HCSs submitted to the same solar flux. Even if some correlations were found between the different parameters that were determined, such as graphitization level, oxygen content and wettability, none of these quantities succeeded in accounting for all observed results.

In contrast, the floatability was the property that allowed understanding all observed trends. It indeed clearly appeared that the evaporation rate increased with the fractional height of the HCS above the water level: see Fig. 2. This was not expected, given that former works rather highlighted the role of the wettability and of the thermal conductivity. The latter assumptions, if correct, would lead to the conclusion that the most graphitized HCS or having met the highest pyrolysis temperature are those having the highest hydrophobicity and the highest thermal conductivity, and hence the highest evaporation rate. But in our case, this fact was only partly observed because of the additional and combined effect of apparent density and roughness, both quantities having a huge impact on floatability. The latter parameter was therefore the one embracing all phenomena.

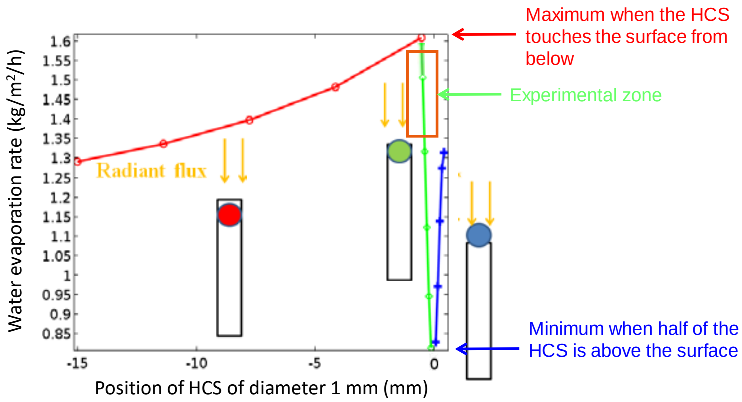

Figure 1. Simulated change of evaporation rate produced by one HCS submitted to 1 kW/m^2 of solar energy, as a function of its position in the water column.

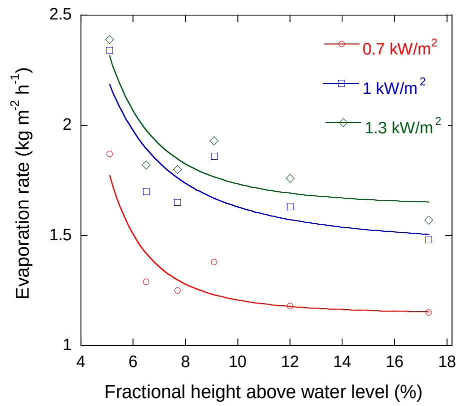

Figure 2. Measured evaporation rate under three different solar energy densities, as a function of floatability.

In order to check this assumption, the evaporation rate was calculated from the model at different positions of the HCS in the water column. Fig. 1 thus clearly shows that the highest evaporation rate is obtained when the HCSs are just beneath but still touching the surface of water from below. When they start to emerge, the evaporation rate decreases due to the decreased area of water available for evaporation, until a deep minimum is reached when half of the HCSs is immersed / emerged. If the HCS are highly hydrophobic, their centers float above the water level, and the evaporation rate increases again with the water area available for evaporation. In our case, the present HCS having the best performances were thus those for which the fractional height above the water level was the lowest (Fig. 2). This is exactly what the simulation given in Fig. 1 shows. The simulation also allowed proving that the effect of thermal conductivity through graphitization has a negligible impact, in contract to what has been postulated in former works.

Conclusion

We have shown the relevance of floating HCSs for boosting the evaporation of water submitted to solar radiation. This is especially true when they poorly emerge above the water level. Such result was obtained as a subtle compromise between wettability (related to graphitization, oxygen content and surface roughness) and apparent density, and all these properties were accounted for by considering the floatability of the HCSs, measured as their fractional height above the water level. Modelling the water evaporation confirmed the major effect of floatability, the highest efficiency being obtained when full HCSs are below the water level but still in contact with the water surface, and the negligible effect of their thermal conductivity.

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