Please cite this article in press as: Li et al., Measuring Conversion Efficiency of Solar Vapor Generation, Joule (2019), https://doi.org/10.1016/j.joule.2019.06.009

Joule

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COMMENTARY

Measuring Conversion Efficiency of Solar Vapor Generation

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Introduction

Solar vapor generation is an appealing technology because it utilizes solar energy and non-potable water (such as sea water, waste water, lake water, etc.), two abundant resources, to generate low-temperature vapor or high-temperature steam for various applications such as water purification, electricity production, sterilization, etc. Recently, interfacial solar vapor generation is drawing significant attention,[1–12] as it provides new pathways for improving the energy conversion efficiency of solar-to-vapor generations.

For sustainable development of this technology, it is critical to accurately evaluate its key figure of merit, the efficiency of solar-to-vapor conversion. The instantaneous efficiency has been generally expressed as $\eta = \dot{m}h_{fg} / P_{in}$,[1] where $\dot{m}$ denotes the evaporation rate ($\dot{m} = \dot{m}_{Light} - \dot{m}_{Dark}$). $\dot{m}_{Light}$ and $\dot{m}_{Dark}$ are the evaporation rate under light and dark conditions, respectively. h_{fg} is the specific enthalpy change of liquid water to vapor, i.e., the enthalpy of vaporization (the dark evaporation rate in this formula will be amended after careful discussion in this manuscript, as discussed later). This efficiency can be intuitively interpreted as the rate of latent energy gained by the vapor divided by the rate of solar energy incident on the device.

While tremendous efforts such as photonic design, heat management, and water supply have been made to increase the conversion efficiency, as of today there is neither systematic description about testing details nor comprehensive study of vital parameters for obtaining the energy conversion efficiency. Consequently, it is difficult and sometimes confusing to evaluate and compare reported efficiencies of solar-to-vapor conversion. In this paper, we first provide general consideration about the indoor testing method and then introduce related precautions from three aspects: light power (P_{in}), evaporation rate ($\dot{m}$), and enthalpy. We hope this paper will facilitate researchers to evaluate the parameters and efficiency more effectively, which provides direct feedback for further exploration of fundamental understanding and practical applications.

General Considerations

To ensure the consistent evaluation of solar vapor generation, a few key elements need to be handled carefully. The evaporation rate of water can be greatly affected by various factors such as temperature, humidity, and wind speed. Thus, to objectively evaluate the performance, testing conditions that can be conveniently reproduced in many parts of the world are recommended. We recommend that the temperature be 25°C, the ambient humidity be under 60%, and the ambient wind be under a breezeless condition (Figure 1). We also recommend that a cylindrical vessel, such as a flat mouth beaker, be used to conduct the experiment. However, the beaker should avoid the role of bottom boundary condition on the heat flux by the liquid (more details are provided in Note S1).

During the testing process, there are another three important distances that can affect the testing results: the distance d_1 between the absorber and the lip of the beaker (Figure 1), the

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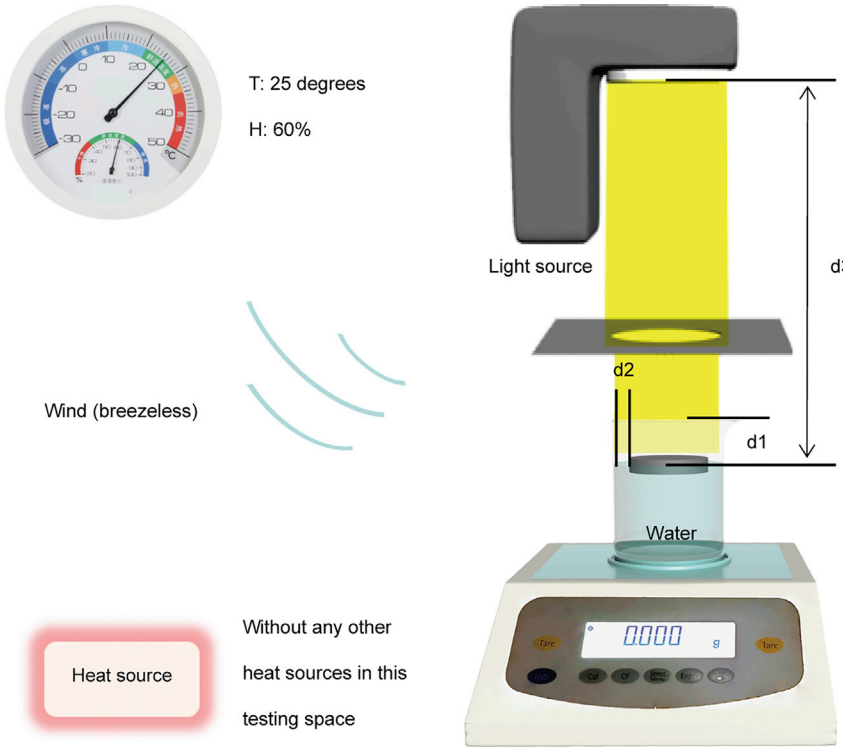

Figure 1. General Considerations for Testing Conditions of Solar Vapor Generation

distance d_2 between the absorber and the beaker wall (Figure 1), and the distance d_3 between the absorber and the light source (Figure 1). It is important to have an appropriate d_1 (typically, smaller is better) so that vapor coming from the absorber will not condense on the beaker sidewall (this can be easily observed in experiments). A large d_2 is undesirable because it will result in extra evaporation due to extra exposed liquid-air interface (a gap size of 1 mm for a 50 mm diameter sample will yield 4% error in the evaporation area). Therefore, d_2 is ideally minimized. As for d_3, it should be long enough to ensure adequate vapor diffusion. The minimum distance is the one above which the rate of mass change of water becomes independent of d_3.

There are some other general precautions. (1) In order to ensure accuracy of testing, it is recommended to have a waiting period after putting samples on the water surface and before light illumination, to ensure that the absorber is fully immersed in the water at the starting point of measurement. (2) There should be no residual water left on the beaker wall, as it will cause extra evaporation under irradiation. (3) A balance (>0.001 g accuracy) without a wind shield is preferred. This is because wind shield may limit the diffusion of vapor by providing an additional mass transfer resistance. (4) Any other heat sources nearby must be removed because of potentially providing extra unaccounted heat input into the evaporation.

Light Power

It is crucial that the input optical power intensity is precisely calibrated. There are two instruments commonly used to measure light intensity: thermopiles and standard silicon solar cells. Thermopiles have a relatively broadband wavelength response (usually wider than 280–2,500 nm). The standard silicon solar cell has very low absorption below its bandgap (~1,200 nm), where nearly a quarter of the solar spectrum resides. Therefore, if there are spikes at long wavelengths (over 1,200 nm) from a light source, the standard silicon solar cell cannot detect them, while a thermopile can. In that regard, we recommend a thermopile be used to measure the input power density. This thermopile should also ideally be calibrated to the light source, as variations in the thermopile reflectivity should be matched to the input spectrum of the light source.

Besides the careful measurement of the light source, there are also many other factors that should be taken into consideration. (1) As shown in Figure 2A, the size of the light spot must be controlled by an aperture (Figure S1), ensuring that it is equal to the size of the absorber. If the illuminated area is too large, the extra irradiation area will heat the environment or the container, potentially providing extra unaccounted heat input into the evaporation area. (2) As shown in Figure 2B, in the light intensity measurement process, it is necessary to ensure that the absorber and light intensity meter are at the same height (the reasons are shown in Note S2). (3) The uniformity of the light spot should also be considered, especially during the calibration process (ideally, the spatial distribution of the irradiance should be mapped—for example, using the method presented by Cooper et al.[2]). (4) It is important to examine whether the power density would remain temporally stable during testing, as the level of water surface at the container decreases because of evaporation.

Commercial solar simulators with xenon bulbs can be acquired with very good spectral conformity and good spatial and temporal uniformity. These are typically labeled as Class A (or AAA) for <2% variation in spatial and temporal uniformity. If commercially certified

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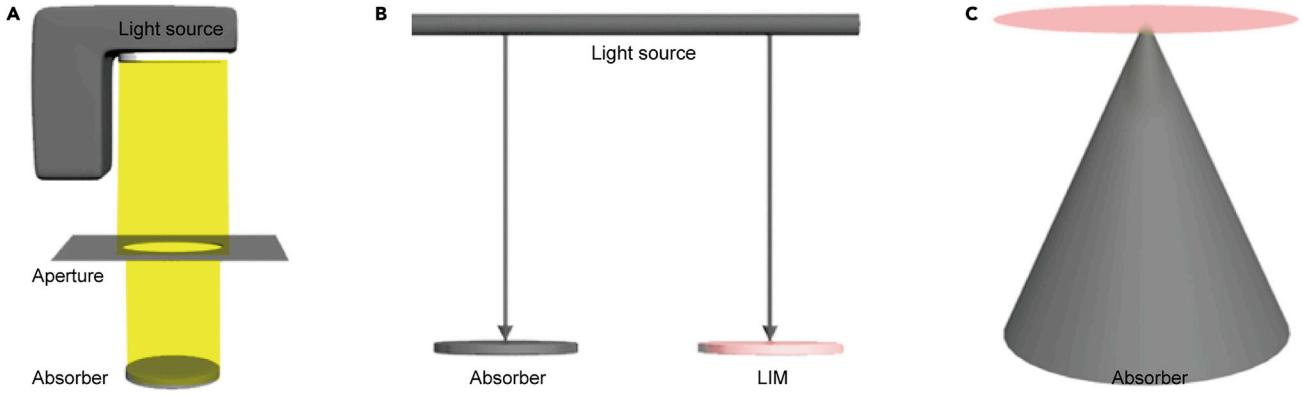

Figure 2. General Considerations about Calibrating the Light Sources

(A) An aperture tightly controls the amount of light incident on an absorber.

(B) Light intensity measurement (LIM) must occur at the same height as the absorber, as the light source often has converging or diverging rays.

(C) Calibration of light power density of a 3D absorber. Red disk represents the top projected plane of the 3D absorber.

solar simulators cannot be acquired, then it would be useful to report the spectral, spatial, and temporal performance.

For 3D absorbers, there are two issues that frequently cause confusion. The first is the light intensity measurement. The second regards the calculation of the absorber area in the efficiency formula. For a 3D absorber, it is recommended to use the top projected plane (as shown in Figure 2C) for the light intensity measurement and the corresponding projected area to calculate the conversion efficiency. The total energy on the top projected area is equal to that received by the absorber under collimated illumination (under non-collimated illumination, the light intensity changes with height over the 3D structure, and it is experimentally difficult to evaluate the total incident light intensity, especially for the power density > 1 sun).

Evaporation Rate

There is some confusion in the field over the proper way to define evaporation rate for the evaporation efficiency calculation. What is generally agreed on is that the standard mass change rate is the slope of the mass change over time (dm/dt) after the testing system reaches a quasi-steady-state, when dm/dt is nearly constant (Figure S2). However, there is not unanimous agreement as to whether the evaporation rate without irradiation ("dark evaporation") should be subtracted. We think that there are mainly two separate cases to consider. In the first case, as shown in Figure 3A, if the temperature of the illuminated absorber is higher than the environment, the dark evaporation should not be subtracted (the justification for this is given in Note S3). 2D[6] or 1D[7] water paths have been widely adopted to reduce heat conduction loss. We recommend that these confined water paths be embedded (Figure 3B) so that dark evaporation out of the water paths can be minimized and neglected. In the second scenario, if only parts of the absorber absorb sunlight, there will be a temperature distribution within the absorber, as shown in Figure 3C. If the temperature of some parts of the absorber is lower than that of the environment, then there will be an energy input from the environment contributing to evaporation (more details are given in Note S3). In this case, dark evaporation should be subtracted to conservatively estimate efficiency. In all cases, measurement of the dark evaporation should preferably still be reported, as it gives valuable insight into the ambient operating conditions, as well as a baseline of comparison to the illuminated evaporation rate.

At this point, there are a few additional precautions related to evaporation rates. (1) If the enthalpy of water remains unchanged, the maximum solar-to-vapor output is around 1.47 kg/m^{2}h under one sun (for details about the calculation, see Li et al.[3]). (2) The absorber itself should be stable, meaning the absorber mass should not change (for example, due to evaporation or decomposition) under irradiation. (3) The area of the absorber should be carefully calculated, especially for irregular-shaped absorbers. Miscalculation can result in large experimental error of evaporation rate. (4) The size of the absorber itself can affect the evaporation rate, as vapor is able to diffuse in multiple directions when leaving smaller absorbers. A shift from centimeter scale to decimeter scale can cause a significant change in the effective evaporation heat transfer coefficient.[4] Hence, care must be taken when extrapolating experimental results from small-area absorbers to large-scale applications.

Enthalpy

In solar vapor generation, there are generally two enthalpy components required for water to transition to vapor. The first part is the sensible heat,

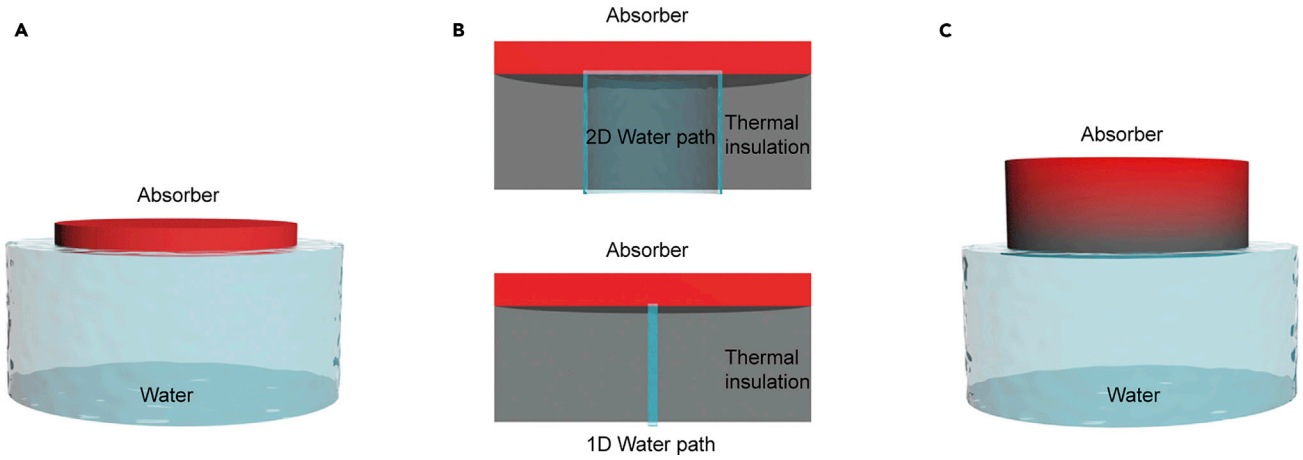

Figure 3. General Considerations for Evaporation Rate and Enthalpy

(A) Solar vapor generation with 2D absorber.

(B) Solar vapor generation with 2D water path and 1D water path.

(C) Solar vapor generation with 3D absorber.

which is the energy difference from T_1 (the temperature of bulk water) to T_2 (the steady-state evaporation temperature). The second part is the phase-change enthalpy, which is the required energy for liquid water at T_2 to form the gaseous phase. We recommend that the sensible heat be taken into account when calculating solar-to-vapor conversion efficiency.

As mentioned above, the evaporation temperature is essential for calculating enthalpy. Typically, two kinds of instruments are used to measure the evaporation temperature: infrared cameras and thermocouples. Each must be used carefully, lest incorrect temperatures be gathered. For infrared cameras, one must consider the intermediate mediums, which may alter or contribute to the thermal radiation emitted by the target. For example, it is common to see infrared cameras pointed at glass beakers to read the temperature of the water contained within. However, glass is opaque to infrared, and the temperatures read by an infrared camera will actually be the glass surface temperature, which can be several degrees cooler than the water. For thermocouples, care should be taken not to introduce additional heat fluxes into the thermocouple tip. When placing a thermocouple onto a solar absorber, the thermocouple will itself absorb sunlight, causing an erroneously high temperature to be recorded, up to a 5°C–10°C difference. Using a reflective or white coating (such as TiO_2, BN, etc.), or by dropping the thermocouple vertically into the absorber, one can avoid heating caused by the solar irradiation. Another approach is to use very fine gauge thermocouples. The convective heat transfer coefficient scales with 1/D while the radiation heat transfer coefficient does not scale with size. Therefore, small thermocouples can minimize radiation error when measuring liquid and gas temperatures.

Others

Currently, with the development of solar vapor technologies, some sealed devices were designed and used in outdoor experiments, such as in lakes and seas, under natural solar irradiation. In this case, we suggest that in addition to providing the above-mentioned solar-to-vapor conversion efficiency, the output, environment and water temperatures, the temporal solar irradiation density, and the ambient wind speed should be provided to fully characterize the outdoor conditions.

Also of note, we provide a checklist (as shown in Note S4) to help make the comparison between different materials and systems more objective.

Conclusions

In summary, we have systematically discussed the general considerations and a few vital parameters related to calculating solar-to-vapor energy conversion efficiency for open-system interfacial solar evaporation structures. These parameters include light power density, evaporation rate, and enthalpy. We also give examples of testing precautions to accurately measure and account for these parameters. In the future, further testing and evaluation of semi-closed systems[2,4] is needed. We hope this paper can help the community with consistent evaluation of the performances, such as energy conversion efficiency, evaporation rate, etc., that will lay down a solid foundation for sustainable development of this booming field of solar vapor generation.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2019.06.009.

ACKNOWLEDGMENTS

We acknowledge the micro-fabrication center of National Laboratory of Solid State Microstructures (NLSSM) for technical support. This work is jointly supported by the State Key Program for Basic Research of China (No. 2015CB659300), the National Key Research and Development Program of China (No. 2017YFA0205700), National Natural Science Foundation of China (Nos. 11621091, 11574143, 61735008), and the Fundamental Research Funds for the Central Universities (Nos. 021314380135, 021314380128).

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https://doi.org/10.1016/j.joule.2019.06.009