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ABSTRACT

In the context of green ships, solar photovoltaic (PV) as an important clean energy technology has attracted the attention of many scholars in the shipping industry. To ensure the stable electrical output of PV modules is the premise for the effective use of solar photovoltaic technology on ships. Different from the terrestrial environment, the disturbance of marine environmental factors to the electrical output characteristics of PV modules should be considered. It is clear that salt spray and seawater are the most important marine environmental factors that affect the electrical output characteristics of PV modules, and the corresponding mechanism is analyzed. A marine environment simulation experimental platform for PV modules is built, and experiment verification is carried out. The results show that salt spray and seawater have different perturbations on the electrical output characteristics of PV modules, and the effects will change with the change of salt spray and seawater. The combined influence of salt spray on the electrical output of the PV module is a maximum power reduction of about 6%, and the combined influence of seawater on the electrical output of the PV module is a maximum power increase of about 20%. The experiment results can provide the research basis for further research on environmental disturbance suppression methods for PV modules.

NOMENCLATURE

A	ideality factor of P–N
C_P	cell dependent properties correction coefficient
d_1, d_2, d_3	experimental factor
G	cell actual solar irradiance (kW/m^2)
G_a	ambient solar irradiance (kW/m^2)
I_m	current at maximum power (A)
I_{sc}	short circuit current (A)
I_{ph}	photo-generated current (A)
I_0	reverse saturation current (A)
k	Boltzmann constant (J/K)
P	power (W)
P_m	maximum power point (W)
q	electron charge (C)
R_s	cell series resistance (Ω)
R_{sh}	cell parallel resistance (Ω)
T	cell actual temperature (°C)
T_a	ambient temperature (°C)
U_{oc}	open circuit voltage (V)
U_m	voltage at maximum power (V)
τ	light transmittance of salt deposition glass
τ_{clean}	light transmittance of clean glass
ω salt	deposition concentration

I. INTRODUCTION

According to the data released by the International Maritime Organization (IMO), NO_x and SO_x emissions generated by the shipping industry account for 14–15% and 4–9% of the global total emissions, respectively, and the shipping industry will account for 12–18% of the global total emissions of greenhouse gas CO_2 in 2050.[1,2] Under the enormous pressure of emission, on the basis of the International Convention on the Prevention of Environmental Pollution from Ships (MARPOL Convention), IMO has put forward a series of mandatory ship energy efficiency rules, so the development of green ships is imperative.[3] In this context, relevant plans, conventions, and strategies have been implemented. Global Trends in Marine Technology 2030 (GMTT 2030), a collaboration among Lloyds Register of Shipping (LR), Quinatic Group and the University of Southampton, lists green and smart ships, sustainable energy production, and energy management as key technologies for the future of the ocean.[4] China attaches great importance to energy conservation and emission reduction. At the General Debate of the 75th Session of the United Nations General Assembly, Chinese President Xi Jinping solemnly declared: "we will strive to reach the peak of carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060." At the same time, China has clearly put forward the national strategy of "making China strong in transportation," developing green transportation and promoting new energy ships in the shipping industry. Therefore, the use of green and clean energy in ships is not only a development trend, but also an urgent one.[5–7]

As one of the most promising clean energy sources in the world, solar photovoltaic is very suitable for the energy supply of ships.[8,9] Since photovoltaic power generation can meet the special requirements of ships such as limited volume and offshore operation, it has been used on ships in many cases, for example, Japanese car carrier "Auriga Leader" and "DRIVE GREEN HIGHWAY," German all-solar powered ship "Turanor Planet Solar," and Chinese car carrier "COSCO TENGFEI."[10–12] Although the application of solar photovoltaic power generation system in large ocean freight ships has great value and prospect, it must be recognized that the particularity of marine environmental will affect its reliability. The PV modules are in direct contact with the marine environmental factors for a long time, which can decrease reliability.[13]

The use of solar photovoltaic power generation system on land is more common, and the related research is more mature. In the terrestrial environment, dust is the main environmental factor to be studied. Domestic and foreign scholars have conducted comprehensive studies on the impact of dust on the reliability of PV module, involving physical properties, influence mechanisms, and formation of dust.[14–17] However, because the application of PV modules in the marine environment is not as common as on land, and the application in large ocean-going cargo ship has only gradually become a research hotspot in the development of green ship technology in recent years, there are many areas that need to be solved urgently in relevant research.

Marine environment contains a lot of salt, water vapor mixed with acid and basic substances, directly acting on the surface of the PV module. Although the PV module glass cover plate is commonly made of low-iron tempered glass, it is also prone to pollution, wear, coloring and corrosion in the environment with high salinity, large temperature difference between day and night, and high humidity for a long time.[18] Because the ocean is a very complex and harsh corrosive environment, researchers focus on the damage caused by seawater corrosion on the surface of PV module. Yuan put forward that under alternating dry and wet conditions, the salt particles are formed on the surface of PV modules, reducing the light transmittance of the glass cover plate and partial shadow effects. Under seawater corrosion, black spots of corrosion on the surface of the glass of PV modules are formed, with further decrease of the spectral transmittance, and even cause irreparable physical damage.[19] Ageev put forward that marine pollution has a great impact on the power generation capacity of the PV module and will form a fouling layer that is not easy to be removed, but it can be treated by coating the surface of the glass cover plate with antifouling coatings.[20] At the same time, US, UK, China, Japan, Australia, South Korea, Singapore, Norway, and other countries have launched the operation of ocean floating photovoltaic power stations. The macroscopic motion caused by wave and seawater corrosion are the key problems to be solved in practical application.[21–23] Although the marine environment is highly corrosive, it takes a long time for tempered glass to be severely corroded. It may be more urgent to pay attention to the influence of marine environmental factors on the electrical output characteristics of the PV module, but the research in this area is still in its infancy. Existing literatures and application examples show that the relevant studies are all about the influence on the reliability after the corrosion of PV modules in the marine environment, including tempered glass and solar cell materials, without directly studying the corresponding relationship between the marine environmental factors and the electrical output characteristics. This is also the innovation of this study.

The electrical output characteristics are the key determinants of PV module energy conversion, which is very important for the use of solar energy in large ocean-going cargo ships. To research the effect of marine environment on the electrical output characteristics of the PV module, some related experiment studies have been carried out on an experimental platform, which can provide references for the application of ship borne PV module.

II. INFLUENCE MECHANISM ANALYSIS

A. Overview of marine environment

The marine environment is very complex and is recognized as one of the most severe corrosion environments, with high humidity, high salinity, and other characteristics. The marine environment can be divided into five corrosion zones: ocean atmosphere zone, seawater splashing zone, seawater tidal range zone, seawater total immersion zone, and sea mud zone.[24,25] PV modules are usually mounted above the deck of a ship, so the ocean atmosphere is their main contact environment. The ocean atmosphere usually refers to the above sea level environment with humidity and high salinity, caused by the evaporation of seawater.[26] At the same time, salt spray and seawater can be attached to the surface of the PV modules on the deck. In the marine environment, salt spray and seawater are the main environmental factors that affect PV modules.

The influence of salt spray and seawater on the PV module is postulated to be a dynamic process, as shown in Fig. 1. The salt spray will form a salt spray layer on the top of the PV module and form a water film on the surface of the PV module. At the same time, the seawater will also cover the surface of the PV module. When the salt spray and seawater evaporate, the salt particles are left on the surface of the glass cover plate. Different coverings on the surface of PV module will have different effects on the electrical output characteristics.

B. Theoretical analysis

The PV module is an energy converter that directly converts radiation energy into electricity. The PV module can be modeled equivalent to a circuit in parallel with a diode and a photogenic current source, and the general purpose solar cell engineering mathematical model can be expressed as follows:[27,28]

$$
\begin{aligned}
I &= I_{\mathrm{ph}} - I_0\left\{\exp\left[\frac{q(U+IR_{\mathrm{s}})}{AkT}\right]-1\right\} - \frac{U+IR_{\mathrm{s}}}{R_{\mathrm{sh}}} \\
I_{\mathrm{ph}} &= \left(\frac{G}{G_0}\right) I_{\mathrm{phG_0}},
\end{aligned} \tag{1}
$$

I_{ph} is the photo-generated current, which is proportional to the solar irradiance. G_0 is 1 kW/m^2 at AM 1.5, and I_{phG0} is the current at G_0.

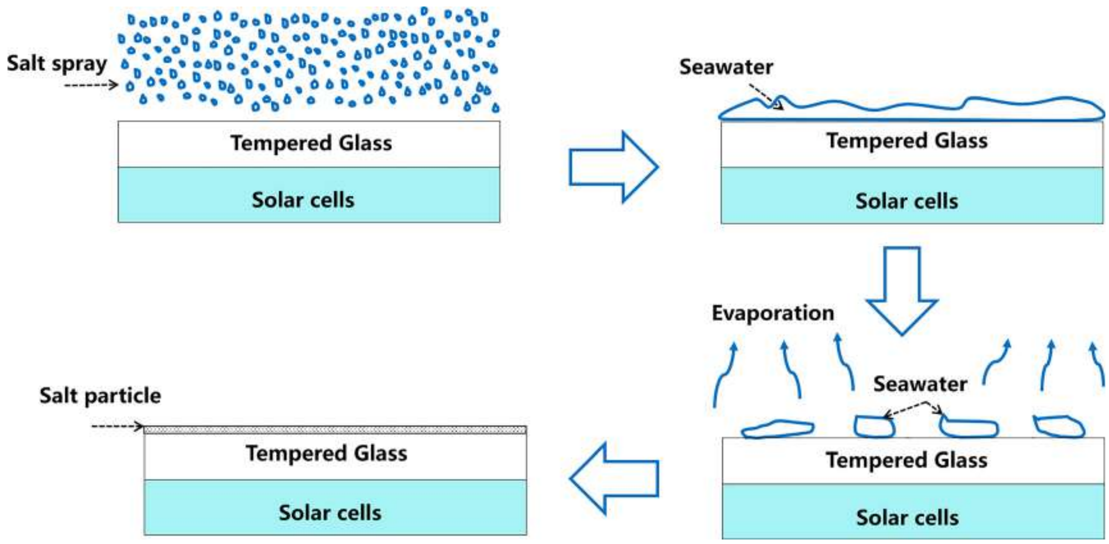

FIG. 1. The changing process of salt spray and seawater.

As observed in Eq. (1), the electrical output characteristic of the PV module is nonlinear, and it strongly varies with cell actual solar irradiance G and cell actual temperature T, which can be expressed as $I = f\ (U,\ G,\ T)$. Therefore, temperature and solar irradiance are the external environmental factors that directly affect the electrical output characteristics of the PV module. Other environmental factors indirectly affect the electrical output characteristics of the PV module by affecting temperature and solar irradiance. To explore the mechanism of the influence of marine environmental factors on the electrical output characteristics of PV module, the relationship between marine environmental factors, temperature, and solar irradiance needs to be further verified by experiments.

The cell actual temperature T is affected by several factors, such as ambient temperature, ambient solar irradiance (before optical losses), cell dependent properties (cell material, plate absorption, etc.), and others. Solar cell actual temperature can be expressed by the following function:[29–31]

$$T = f(T_a, G_a, C_P). \tag{2}$$

The cell actual solar irradiance G is affected by the ambient solar irradiance, cell dependent properties (surface characteristics, glazing cover transmittance, etc.), and others. The actual intensity of solar irradiance received by the solar cell can be expressed by the following function:[32–34]

$$G = f(G_a, C'_P). \tag{3}$$

It can be found from Functions (2) and (3) that the electrical output characteristics of PV module can be represented by the following function:

$$I = f(U, G_a, T_a, C_P). \tag{4}$$

It can be found from Function (4) that there is a relationship between the influencing factors corresponding to the relevant parameters and the marine environment.[35,36]

C. Influencing mechanism of marine environmental factors

Salt spray and seawater are the main factors that affect the PV module in the marine environment. Based on their characteristics and Function (4), the mechanism of their influence is actually realized by changing temperature and radiation intensity.

For the influence of salt spray on PV module, the water mist with a lot of salt manifests as a salt spray layer on the top of PV module. Scattering and absorption of the salt spray will have an impact on the actual solar irradiance received by the PV module. At the same time, salt spray is more likely to evaporate and carry away heat, thus affecting the temperature of PV module.

The influence of seawater on the PV module mainly comes from the water film formed on the surface. The evaporation of seawater will affect the heat dissipation. At the same time, seawater on the surface of the PV module will affect the absorption of solar irradiance.

To further verify the influence mechanism, it is necessary to build an experimental platform to carry out verification.

III. EXPERIMENTS

A. Experimental platform

Since the existing PV module experimental platform cannot effectively carry out marine environmental impact research, the researchers designed an experimental platform suitable for relevant experiments according to the characteristics of the shipboard environment. The experimental platform consists of a main work box, a sample holder, a modular lighting system, a water circulation system, and so on, which are shown in Fig. 2. The dimensions of the main work box are $1.5 \times 1 \times 0.8$ m, and it is closed in the experiment. The PV modules are mounted horizontally on the sample holder. The solar irradiance is provided by artificial modular lighting system, which consists of a xenon lamp AHD3000W (AC 220 V $\pm$ 20 V, 50 Hz, 3 kW, spectral grade AM1.5 Class B/A, spectral range 280–3000 nm, irradiation range 200–1000 W/m^2, irradiation uniformity within $\pm$5%) and

FIG. 2. Experimental platform.

tungsten lamps (150 W × 12, matrix arrangement). The water circulation system consists of centrifugal cross spray devices (spray rate 20–60 l/h, aerosol particles diameter 20–30 μm), a miniature diaphragm pump DP-60 (DC 24 V, 40 W), and a water tank (cube, 150 l).

The monitoring system of the experimental platform is responsible for collecting and recording experiment data and controlling vibration frequency and other experiment operation parameters. A temperature and humidity sensor STH-W2 (measurement error: temperature ±0.3 °C, humidity ± 2%RH), a patch type temperature sensor JCJ100TTP (measurement error ±0.3 °C), and a total radiation sensor PHFB-JZF (sensitivity 7–14 μV/W·m^{-2}) are used to collect environmental parameters such as temperature, humidity, and solar irradiance. A solar output characteristic tester PROVA210 (measuring accuracy: voltage 0.001 V, current 1 mA) is used to test the PV module characteristics, including the maximum power operating point, the corresponding maximum voltage and current, the open circuit voltage, and the short circuit current.

B. Experimental condition

The temperature and solar irradiance are the external environmental factors that directly affect the electrical output characteristics of PV module, while other environmental factors mainly indirectly affect the electrical output characteristics by changing the cell actual temperature or the received solar irradiance. To explore the influence of the marine environment on the electrical output characteristics of PV module, this paper verified the relationship between seawater, salt spray, temperature, and solar irradiance through the experimental platform. The PV module GH-10 W is taken as the research object, and the specification parameters are listed in Table I.

The average salinity of seawater in the world's oceans is about 3.5%, and the pH value ranges from 7.9 to 8.4, which will vary according to different sea and weather conditions. This study uses sea crystal as the main raw material to prepare artificial seawater with a concentration of 3.5% and a pH value of 8.2. According to the annual average solar irradiance distribution on the Earth's surface published by NASA,[37,38] the solar irradiance simulated by the artificial modular lighting system is set at 800 W/m^2.

C. Experimental procedure of salt spray

The effects of salt spray on the electrical output characteristics of PV module are tested, which are shown in Fig. 3. Artificial seawater with concentration of 3.5% and pH value of 8.2 is tested, while clear water and artificial seawater with concentration of 10% and pH value of 8.2 are selected as comparison. The initial ambient temperature of the experiments is controlled by the heating device of the experimental platform, so that the temperature is stable. The salt spray is supplied by the water circulation system at a rate of 30 l/h. The electrical output characteristics of PV modules while adding salt spray with different concentrations are measured under continuous solar irradiance. Three evaluation parameters are introduced to quantitatively analyze the variation trend of electrical output characteristics, which are selected as U_{oc}, I_{sc}, and P_m. The temperature of the PV modules and the solar irradiance are obtained simultaneously.

TABLE I. Technical data of PV module.

Model	P/W	U_{oc}/V	I_{sc}/A	U_m/V	I_m/A
GH-10W	10	21.6	0.67	17.6	0.57

FIG. 3. Salt spray experiment.

D. Experimental procedure of seawater

The electrical output characteristics of the PV modules under continuous solar irradiance are tested, respectively, while covering the PV modules surface with water of the same three salinity concentrations as in the salt spray experiment, which are shown in Fig. 4. We obtain multiple sets of data over a period of time and ensure the evaporation of seawater with salt particles left in the total amount of time measured. Three evaluation parameters are selected for quantitative analysis, which are U_{OC}, I_{SC}, and P_m. The temperature change data of the PV modules are obtained.

IV. EFFECT OF SALT SPRAY AND SEAWATER

A. Experimental analysis of salt spray

Under continuous solar irradiance, the water pump is turned on 10 min after the start of the experiment, and salt spray is sprayed into the experimental platform by the centrifugal cross spray devices. After the spraying process lasts for 15 min, the water pump is turned off, and salt spray spraying stops. The results of experiment are shown in Fig. 5. The situations for each phase are shown in Table II.

According to the results shown in Fig. 5, in the early stage of the experiment, under continuous solar irradiance, U_{OC} and P_m of the PV module continued to decrease, while I_{SC} increased slightly based on data in Phase 1. In Fig. 5(d), it can be seen that the temperature of PV modules increases due to solar irradiance. The increase in temperature will decrease the energy of the semiconductor P–N junction bandgap and lead to more valence electrons capable of transition, thus generating more electron–hole pairs, resulting in an increase in short-circuit current, but the change is weak. At the same time, it will significantly reduce the open-circuit voltage and the maximum power point.

After the salt spray is injected, Fig. 5(d) shows that over time, the temperature of the PV modules begins to drop in phase 2. We hypothesize that the temperature decrease is caused by evaporation of salt spray with heat. While cooling should increase solar cell efficiency, the

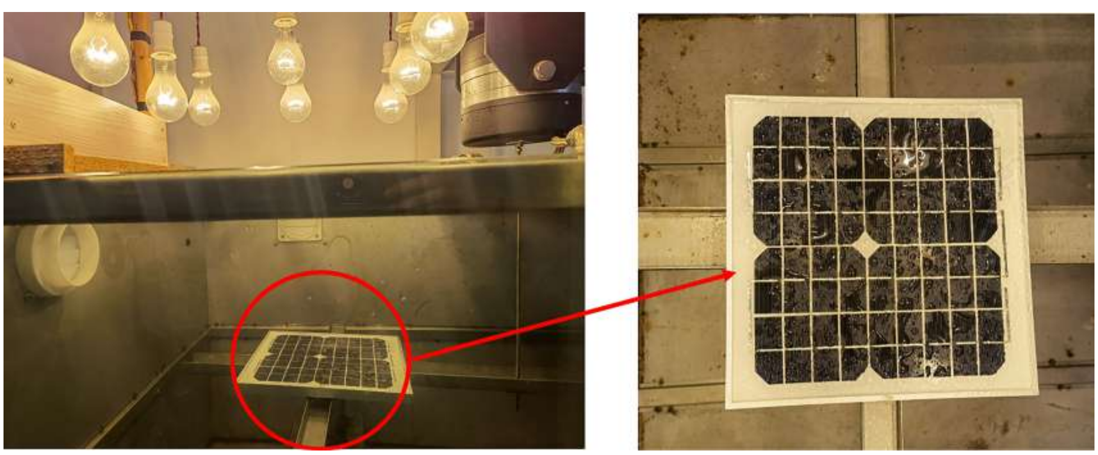

FIG. 4. Seawater experiment.

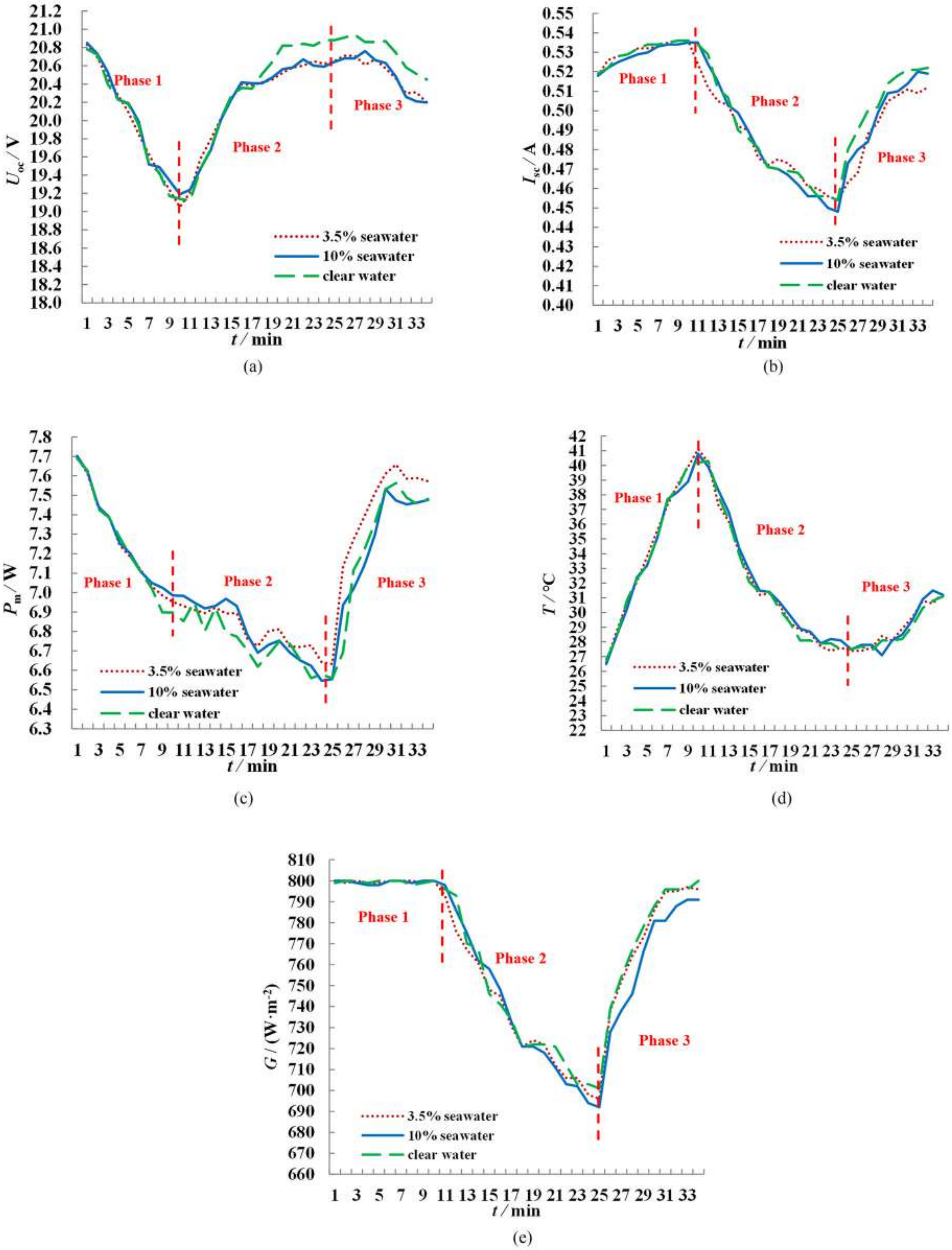

FIG. 5. Electrical output in salt spray experiment with (a) the open circuit voltage (U_{oc}), (b) the short circuit current (I_{sc}), (c) the maximum power point (P_m), (d) the cell temperature (T), and (e) the cell solar irradiance (G).

TABLE II. The situation for each phase in salt spray experiment.

Phase	U_{oc}	I_{sc}	P_m	T	G
1	↘	↗	↘	↗	↘
2	↗	↘	↘	↘	↘
3	↘	↗	↗	↗	↗

results in Fig. 5(c) show that P_m does not increase, but continues to decrease. Figure 5(e) shows the change of the irradiation of the artificial light source after passing through the salt spray layer to the PV module. The irradiation reaching the surface of the PV modules is reduced significantly after the salt spray is sprayed. Therefore, we conclude that the scattering and absorption of irradiation by the sea salt spray results in a significant reduction in the actual solar irradiance received by the PV module. This weakening effect has a stronger impact on the electrical output of the PV modules than the positive effect brought by cooling, resulting in the decreasing power output shown in Fig. 5(c). As shown in Figs. 5(a) and 5(b), U_{oc} increases and I_{sc} decreases after salt spray spraying. The reduction of irradiation has a weak influence on U_{oc}, while it has a strong weakening effect on I_{sc}, which is different from the output changes caused by temperature. This also shows that salt spray has a stronger weakening effect on irradiation.

When the salt spray stops spraying, the solar irradiance received by the PV modules increases, causing a significant increase in P_m and I_{sc} in phase 3. The above results also confirm that the effect of salt spray on solar irradiance is greater than that of temperature. According to Function (4), the main factors affecting salt spray are surface characteristics.

Comparing the results of the three experiments of clear water, salt spray with 3.5% concentration, and salt spray with 10% concentration, the measurements are similar, indicating that the effect of salt spray is mainly based on the effect of water spray on solar irradiance and heat dissipation, and the change of salinity will not make a significant difference in the results. The combined influence of water spray on the electrical output characteristics of PV module manifests as a maximum power reduction of about 6% based on data in phase 2. When the PV modules are used in inland rivers and other areas with easy to condense water, the water mist generated in the environment will also have a similar influence on the electrical output characteristics.

B. Experimental analysis of seawater

Artificial seawater is sprayed on the surface of the PV module after 20 min of experiment under continuous solar irradiance, and the results of experiment are shown in Fig. 6. The situations for each phase are shown in Table III.

The electrical output of the PV modules is consistent with the results shown in Fig. 5 before spraying seawater on the surface in phase 1. The temperature of the PV modules increases gradually under continuous solar irradiance, which leads to a decrease in U_{oc} and P_m, with a slight increase in I_{sc}. When the seawater is sprayed, the temperature of the PV modules drops significantly, indicating that the seawater attached to the surface of the PV modules has a good cooling effect due to evaporation and heat absorption. At the same time, the water

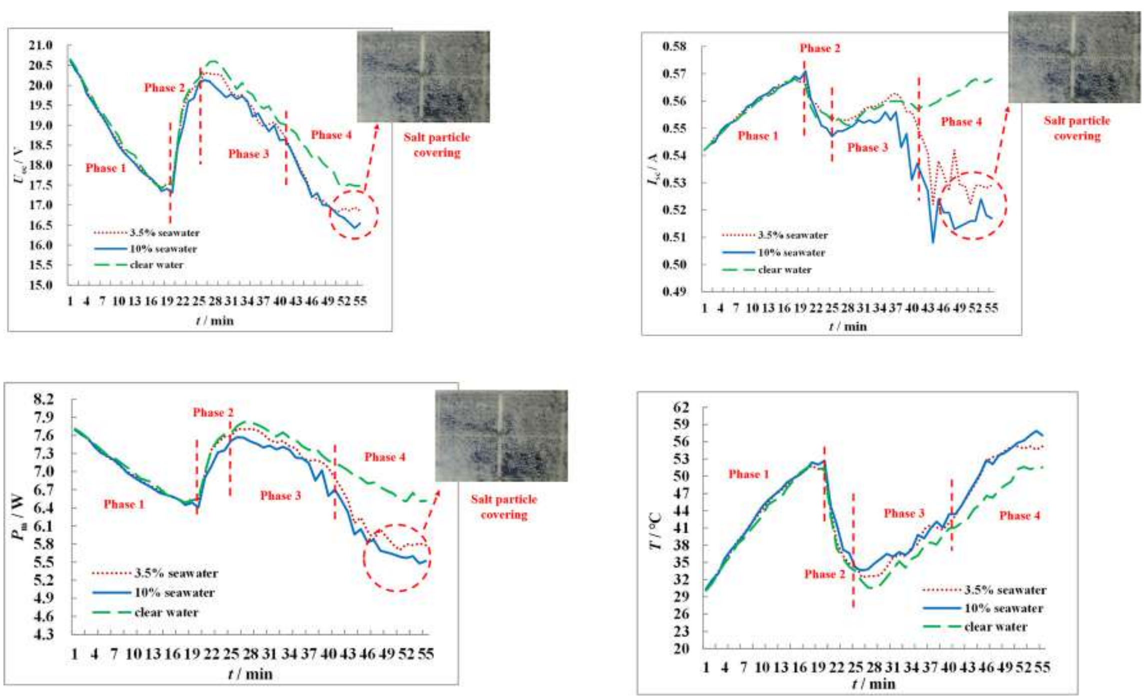

FIG. 6. Electrical output in seawater experiment with (a) the open circuit voltage (U_{oc}), (b) the short circuit current (I_{sc}), (c) the maximum power point (P_m), and (d) the cell temperature (T).

TABLE III. The situation for each phase in seawater experiment.

Phase	U_{oc}	I_{sc}	P_m	T
1	↘	↗	↘	↗
2	↗	↘	↗	↘
3	↘	↗	↘	↗
4	↘	↘	↘	↗

can cause the solar irradiance, hitting the surface of the PV modules to reflect and refract, and affecting the intensity of the radiation the solar cell receives. Figures 6(a)–6(c) show that the combined effect of temperature and solar irradiance changes caused by seawater, P_m and U_{oc}, significantly increase, while I_{sc} weakly decreases, indicating that seawater mainly increases the output of the PV module through cooling. The combined influence of seawater on the electrical output of PV module manifests in a maximum power increase of about 20% in the early stage based on data in phase 2.

After about 40 min, Fig. 6(d) shows that the temperature of the PV modules begins to rise significantly, and the output parameters, including U_{oc}, I_{sc}, and P_m, all show a significant decrease in phase 4. Observing the PV modules, except for the PV modules sprayed with clean water, the glass surface of the other PV modules is originally clean and transparent, but becomes gradually covered with some white crystals. The surface pollution of the PV modules sprayed with 10% concentration artificial seawater is more serious than that with 3.5% concentration artificial seawater. We hypothesize that as the water evaporated, salt crystals gradually attach to the PV module surface, causing extinction of solar irradiance for the PV module. The salt deposition also causes the solar irradiance spread uniformity on the glass cover to change, thereby causing loss to the extra reflective. As a material with a low thermal conductivity, salt particles block the heat transfer of PV module, making it difficult for the PV module to release its own heat, leading to a temperature rise. The combined effect of the two effects results in a significant weakening of the electrical output of the PV module. The combined influence of salt particles left by 3.5% concentration artificial seawater is a maximum power reduction of about 10%. The 10% concentration artificial seawater precipitates more salt particles and covers more area, which exacerbates the salt deposition effect and the power reduction. Since there is no salt particle left after evaporation of clear water, the result differs from artificial seawater in the later stage of the experiment. The experimental results agree with the theoretical hypothesis, which is shown in Fig. 1. According to Function (4), the main factors affecting seawater are surface characteristics.

Foreign bodies cover PV modules in the form of uniform coverage or local accumulation, and the effect of local shadow is different due to the different forms of coverage. As shown in Fig. 7, salt is evenly covered like dust in the process of deposition increment. It can be deemed that the existence of salt particles weakens the light transmission of the glass cover plate of PV module as a whole. According to Eq. (1), G is actually reduced.

According to Fig. 6, before and after salt deposition, the temperature rising trend changed little. With reference to the relation between dust deposition and light transmittance reduction, the influence of salt deposition increment on light transmittance can be characterized as follows:

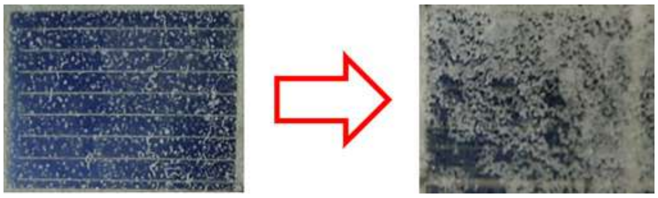

FIG. 7. Process of salt deposition increment.

$$\left(1-\frac{\tau}{\tau_{\text{clean}}}\right)\% = d_1 erf\left(d_2\omega^{d_3}\right), \tag{5}$$

where erf is the error function and τ affects G. The determination of experimental factors d_1, d_2, d_3 is related to the seawater concentration and weather variables (ambient temperature, wind velocity, etc.), which affect the evaporation rate. In an actual application, Eq. (5) can be used for quantitative calculation combined with environmental characteristics.

Meanwhile, in experiment 1, liquid water remained on the surface of the PV modules after the salt spray is stopped, which is similar to what happened after the artificial seawater is sprayed on the surface of the PV modules in experiment 2. Comparison of the results shown in Figs. 5(d) and 6(d) shows that the temperature of PV modules in experiment 1 still gradually rises when there is water on the surface in phase 3, and the temperature in experiment 2 also gradually rises after a relatively short period of the seawater cooling in phase 3. Therefore, this paper believes that although the cooling effect of seawater attached to the surface of PV module is obvious, it will be temporary if there is no subsequent seawater scouring.

V. SUMMARY AND CONCLUSION

Through theoretical analysis and related experiments, the influence of the marine environment on the electrical output characteristics of PV modules is studied. It can be concluded that there are differences between the effects of salt spray and seawater on the electrical output characteristics. The following conclusions can be drawn:

(1) The influence of salt spray and seawater on PV module is a dynamic process. They affect the solar irradiance and temperature received by the solar cell through changing the surface conditions of the PV module, thus changing the electrical output characteristics.
(2) Salt spray reduces the solar irradiance received by PV module to a higher degree than the cooling effect. The combined influence of salt spray on the electrical output of the PV module is a maximum power reduction of about 6%.
(3) The cooling caused by the seawater attached to the surface of the PV module plays a major role in the early stage. The combined influence of seawater on the electrical output of the PV module is a maximum power increase of about 20%. However, the evaporation of seawater will cover the glass surface of PV module with salt particles, thus causing shielding and reducing the absorbed irradiance. Salt is evenly covered like dust in the process of deposition increment. At the same time, the salt particles also promote temperature rise, which will significantly reduce the output of PV modules. The combined influence of

salt particles on the electrical output of the PV module is a maximum power reduction of about 10%.

(4) In real marine environments, salt spray and seawater usually coexist. Salt spray formation water film, water evaporation, and precipitation of salt particles occur at the same time. The resulting changes to the PV module output are often very complex, and it can lead to increases or decreases in the PV module output. Meanwhile, considering the rain, salinity of seawater, and other factors, the salt deposition will be slower, which will also affect the PV module output. Further research is needed.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1]International Maritime Organization (IMO), *The International Maritime Organization's Initial Greenhouse Gas Strategy* (IMO's Marine Environment Protection Committee (MEPC), London, 2018).
[2]See Center for Climate and Energy Solutions (C2ES), https://www.c2es.org/content/international-emissions for "Global Emissions [EB/OL]" (last accessed June 05, 2020).
[3]J. A. Felicio, R. Rodrigues, and V. Caldeirinha, "Green shipping effect on sustainable economy and environmental performance," Sustainability **13**(8), 4256 (2021).
[4]Lloyd's Register, *Global Marine Technology Trends 2030* (QinetiQ and University of Southampton, 2015).
[5]Japan Ship Technology Research Association, *Roadmap to Zero Emission from International Shipping* (Supported by Shipping Zero Emissions Project, Japan, 2020).
[6]S. Chu and A. Mujumdar, "Opportunities and challenges for a sustainable energy future," Nature **488**(7411), 294–303 (2012).
[7]P. C. Pan, Y. W. Sun, C. Q. Yuan *et al.*, "Research progress on ship power systems integrated with new energy sources: A review," Renewable Sustainable Energy Rev. **144**, 111048 (2021).
[8]C. Nuchturee, T. Li, and H. P. Xia, "Energy efficiency of integrated electric propulsion for ships—A review," Renewable Sustainable Energy Rev. **134**, 110145 (2020).
[9]Y. Q. Zhu, S. Zhou, Y. M. Feng *et al.*, "Influences of solar energy on the energy efficiency design index for new building ships," Int. J. Hydrogen Energy **42**(30), 19389–19394 (2019).
[10]C. Karatug and Y. Durmusoglu, "Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: A case study," Sol. Energy **207**, 1259–1268 (2020).
[11]J. L. Teeter and S. A. Cleary, "Decentralized oceans: Sail-solar shipping for sustainable development in SIDS," Natural Resour. Forum **38**(3), 182–192 (2014).
[12]T. Kokusho, E. Emoto, and T. Kato, "Sailing solar-cell raft project and weather and marine conditions in low-latitude Pacific Ocean," J. Energy Eng. **139**(1), 2–7 (2013).
[13]L. Chen, J. D. Wang, and C. X. Xu, "The application of solar photovoltaic power generation system in ships," J. Coastal Res. **94**, 525–529 (2019).
[14]X. Q. Liu, S. Yue, L. Y. Lu *et al.*, "Investigation of the dust scaling behaviour on solar photovoltaic panels," J. Cleaner Prod. **295**, 126391 (2021).
[15]H. F. Varga and M. R. Wiesner, "Effect of dust composition on the reversibility of photovoltaic panel soiling," Environ. Sci. Technol. **55**(3), 1984–1991 (2021).
[16]X. Q. Liu, S. Yue, J. L. Li *et al.*, "Study of a dust deposition mechanism dominated by electrostatic force on a solar photovoltaic module," Sci. Total Environ. **754**, 142241 (2021).
[17]Z. A. Darwish, K. Sopian, and A. Fudholi, "Reduced output of photovoltaic modules due to different types of dust particles," J. Cleaner Prod. **280**, 124317 (2021).
[18]J. Xu and J. Bu, "Preparation and properties of solar composite materials for marine environment," Appl. Ecol. Environ. Res. **17**(6), 14217–14229 (2019).
[19]C. Q. Yuan, C. L. Dong, L. L. Zhao *et al.*, "Marine environmental damage effects of solar cell panel," in International Conference on Prognostics and Health Management, Macau (2010).
[20]M. D. Ageev, D. R. Blidberg, J. Jalbert *et al.*, "Results of the evaluation and testing of the solar powered AUV and its subsystems," in Symposium on Autonomous Underwater Vehicle Technology, San Antonio, TX, USA (2002).
[21]H. D. Liu, Q. Zhang, X. X. Qi *et al.*, "Estimation of PV output power in moving and rocking hybrid energy marine ships," Appl. Energy **204**, 362–372 (2017).
[22]N. Espinosa, M. Hosel, M. Jorgensen *et al.*, "Large scale deployment of polymer solar cells on land, on sea and in the air," Energy Environ. Sci. **7**(3), 855–866 (2014).
[23]M. Hossain, S. Mekhilef, and L. Olatomiwa, "Performance evaluation of a standalone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia," Sustainable Cities Soc. **28**, 358–366 (2016).
[24]F. L. Qu, W. G. Li, W. K. Dong *et al.*, "Durability deterioration of concrete under marine environment from material to structure: A critical review," J. Build. Eng. **35**, 102074 (2021).
[25]H. Y. Liu, Y. X. Teng, J. Guo *et al.*, "Corrosion resistance and corrosion behavior of high-copper-bearing steel in marine environments," Mater. Corros. **72**(5), 816–828 (2020).
[26]R. M. Katona, R. G. Kelly, C. R. Bryan *et al.*, "Use of *in situ* Raman spectroelectrochemical technique to explore atmospheric corrosion in marine-relevant environments," Electrochem. Commun. **118**, 106768 (2020).
[27]S. R. Wenham, M. A. Green, and M. E. Watt, *Applied Photovoltaics* (Earthscan, UK/USA, 2007).
[28]R. Kadri, H. Andrei, and J. P. Gaubert, *et al.*, "Modeling of the photovoltaic cell circuit parameters for optimum connection model and real-time emulator with partial shadow conditions," Energy **42**(1), 57–67 (2012).
[29]S. Mekhilef, R. Saidur, and M. Kamalisarvestani, "Effect of dust, humidity and air velocity on efficiency of photovoltaic cells," Renewable Sustainable Energy Rev. **16**(5), 2920–2925 (2012).
[30]F. G. Al-Amri and T. I. M. Abdelmagid, "Analytical model for the prediction of solar cell temperature for a high-concentration photovoltaic system," Case Stud. Therm. Eng. **25**, 100890 (2021).
[31]D. Kumar and A. K. Tangirala, "Adaptive model predictive control of module temperature in photovoltaic systems," Ind. Eng. Chem. Res. **60**(11), 4351–4365 (2012).
[32]N. Anani and H. Ibrahim, "Adjusting the single-diode model parameters of a photovoltaic module with irradiance and temperature," Energies **13**(12), 3226 (2020).
[33]C. F. Abe, J. B. Dias, G. Notton *et al.*, "Experimental application of methods to compute solar irradiance and cell temperature of photovoltaic modules," Sensors **20**(9), 2490 (2020).
[34]C. F. Abe, J. B. Dias, G. Notton *et al.*, "Computing solar irradiance and average temperature of photovoltaic modules from the maximum power point coordinates," IEEE J. Photovoltaics **10**(2), 655–663 (2020).
[35]H. E. Achouby, M. Zaimi, A. Ibral *et al.*, "New analytical approach for modelling effects of temperature and irradiance on physical parameters of photovoltaic solar module," Energy Convers. Manage. **177**, 258–271 (2018).
[36]Y. Imai, J. Chantana, Y. Kawano *et al.*, "Description of performance degradation of photovoltaic modules using spectral mismatch correction factor under different irradiance levels," Renewable Energy **141**, 444–450 (2019).
[37]M. T. DeLand, G. Kopp, and D. B. Considine, "Overview of the NASA Solar Irradiance Science Team (SIST) program special section," Earth Space Sci. **6**(12), 2229–2231 (2019).
[38]M. Trolliet, J. P. Walawender, B. Bourles *et al.*, "Downwelling surface solar irradiance in the tropical Atlantic Ocean: A comparison of re-analyses and satellite-derived data sets to PIRATA measurements," Ocean Sci. **14**(5), 1021–1056 (2018).