

Insight into tribological problems of green ship and corresponding research progresses

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Abstract: The so-called “green ship” is being regarded as a potential solution to the problems that the shipping industry faces, such as energy conservation and environmental protection. Some new features, such as integrated renewable energy application, biomimetic materials, and antifriction and wear resistant coating have been accepted as the typical characteristics of a green ship, but the tribology problems involved in these domains have not been precisely redefined yet. Further, the related research work is generally focused on the technology or material itself, but not on the integration of the applicable object or green ship, marine environment, and tribological systematical analysis from the viewpoint of the energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP) improvements. Aiming at the tribology problems of the green ship, this paper reviews the research status of this issue from three specific domains, which are the tribology problems of the renewable energy system, tribological research for hull resistance reduction, and energy efficiency enhancement. Some typical tribological problems in the sail-auxiliary system are discussed, along with the solar photovoltaic system and hull drag reduction in traditional marine mechanical equipment. Correspondingly, four domains that should be further considered for the future development target of the green ship are prospected.

Keywords: green ship; tribology; renewable energy; biomimetic material; ship drag reduction

1 Introduction

The shipping industry is a significant segment of the comprehensive transportation system. According to the report “Review of Maritime Transport”, it was stated that the total amount of global maritime trade was 7.84 billion tons in 2009, and a market share of 80% of the global flow of goods was transported by sea [1]. In addition, it was estimated in 2015 that the world seaborne trade volume surpassed 10 billion tons [2] for the first time in the records of the United Nations Conference on Trade and Development (UNCTAD). However, once regarded as the most

environmental friendly mode of transport, as global warming and environmental pollution are considered problems of globalization, the shipping industry has inevitably been pushed into the focus point of public opinion. Statistical data shows that the volume of greenhouse gases, polluting gases, and particle contamination (CO₂, SO_x, NO_x, and PM) discharged by ships is growing distinctly in recent years, and other problems such as the uneven distribution of energy resources, growing energy demand, and high fuel costs are all a direct pressure forcing the shipping industry to explore a new direction for its future development. In this context, the targets of energy conservation and

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emission reduction are widely accepted as a kind of social responsibility by the global shipping enterprises, and gradually, some new technologies and/or materials that have the typical green factor properties are applied on ships for this purpose [3]. These technologies include, for example, renewable technologies (wind power, solar power, fuel cells, gas as fuel, etc.), low-carbon lubrication materials, tribological and biomimetic materials, and antifriction and wear resistant coating. However, the related research work is generally focused on the technology or material itself, but not on the integration of the applicable object or green ship, marine environment, and tribological systematical analysis. In this paper, the tribology problems of the green ship are classified into two categories, external and internal friction, from a systematical standpoint, and the corresponding research progress is discussed from three specific domains, which are the tribology problems of the green ship, tribological research for hull resistance reduction, and energy efficiency improvement.

2 Green ship and tribology

The concept of green ship, which firstly appeared in the mid-1990s, means the application of advanced technology to satisfy the targeted function and performance of mechanical equipment, improve the efficiency of energy utilization, and reduce and/or eliminate environmental pollution during the total life cycle of the ship. Further, the green ship designed and built based on this innovative concept must provide the crews with proper personal protection. To promote the development process of the green ship, the International Maritime Organization (IMO) and the classification societies in each country (e.g., China Classification Society, LR Lloyds Register of Shipping, and NK Nippon Kaiji Kyokai) have established a series of industry guides, specifications, and technical standards [4]. Two vital standards, the energy efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP), aiming at compulsorily implementing the policy of greenhouse gases emission for all ships, were authorized by the Marine Environment Protection Committee (MEPC) of the IMO in its 62nd session. Afterwards, many

classification societies have started to push forward their own criteria, as follows: (1) Environment and energy efficiency grade scheme, by Det Norske Veritas (DNV); (2) independent certificate of green passport for both new and operating ships, by Lloyd's Register group (LR); (3) environmental service system, by Germanischer Lloyd group (GL), for the special service of customers' environmental requirements [5]; (4) the China Classification Society (CCS) has set a special mark and divides it into three levels according to the green factors included, namely, the additional certification of green ship. Besides, various kinds of frontier and advanced concepts have been used to design and build the green ship, wherein many technical fields are being involved, from the optimization of hull structure to high efficient power and propulsion system, and from the high strength ship steel to coating that is pollution-free. It is believed that the ship that integrates the green factors or green technologies all together will become the development trend for green ships in the near future.

The tribology theory, which concentrates on the contact mechanics of moving interfaces, which generally involve energy dissipation [6], has been widely utilized to analyze the energy efficiency and economic feasibility of a ship. According to the study report "Second IMO GHG Study 2009" [7], the research data based on a contrastive case study was represented to understand the relationship between energy losses and friction effect that is involved in marine equipment. The main reasons leading to energy losses are classified as seven factors among four typical ship forms, as it is shown in Fig. 1. About 37.6% (mean value) of the energy from the fuel is spent to overcome diverse types of resistance, which have direct and/or indirect relationship to tribological problems. Comprising air and hydraulic resistance, the hull resistance is the main cause among the eight cases. Its maximum percentage, 17.2%, corresponds to the second case. The propulsion transmission losses, propeller frictional losses, and wave generation are the areas that constitute the second highest proportion. In the fifth case, its peak value accounts for 19.2% of the total energy losses, even more than that of the hull resistance. Moreover, the factors of weather and waves should be taken into the tribology considerations regarding energy

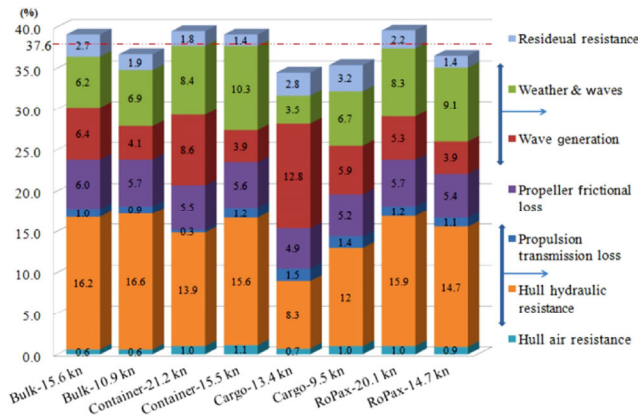


Fig. 1 Distribution of energy losses (%) involving tribology problems in selected case ships.

losses, but its total percentage may be directly changed by utilizing a reasonable navigation program. Ships other than the eight cases shown in Fig. 1 have the same types of energy dissipation. The only difference is that their relative values will differ. The most notable point is that the research target of tribology is being changed from the traditional concept of friction control (wear reduction and lubrication improvement) to that of energy efficiency and environmental friendliness [8], e.g., energy conservation, emission reduction, low noise and vibration, ecological lubrication, and high quality of life.

In view of the issues mentioned above, the tribology problems involved in the green ship technology can be divided into two parts, which are defined in this paper as the external and internal friction. The former is located at the interface between the hull and water, whereas the latter points to the frictions that occur in the main engine, auxiliary machinery, and shafting system. The key issues included in these two categories can be further classified and studied in three main aspects, as shown in Fig. 2.

3 Tribological problem of renewable energy system

New energy is not a kind of energy source, but rather a technical system to utilize the renewable energies from the viewpoint of cleanliness, efficiency, and systematization. Some typical new energy technologies have shown their potential advantages not only in experimental research but also for commercial applications serving as demonstration cases [9].

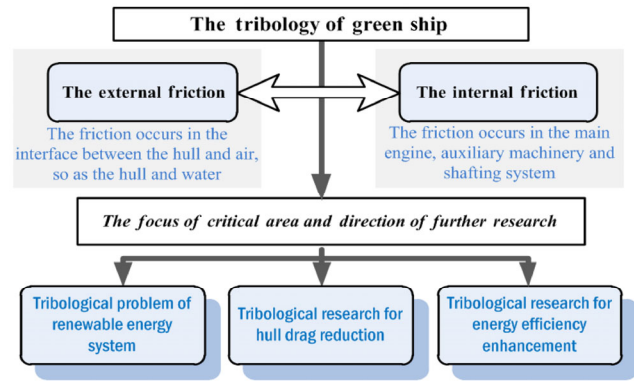


Fig. 2 Theoretical frame for the tribology of green ship.

Figure 3 shows the successful utilization of some typical new energy systems in the green ship, such as wind, solar, nuclear power, fuel cells, tidal power, hydrogen, and biomass. However, some critical issues still need to be paid attention to, especially when dealing with the promotion of the green ship program based on the concepts of systematization and standardization, e.g., the characteristics and utilization method of each energy type vary if applied in different ship platforms, as mentioned above. Other influencing factors, such as hull structure, power and electrical system, crew configuration, navigation area, and port logistics, should be analyzed comprehensively according to the extent of their potential effect, and be arranged during the designing and building process.

From a systematic perspective, the majority of primary energy sources (new or renewable energies) cannot be directly utilized as the power driving the electrical and propulsion systems, unless they are transformed into secondary energy sources by an energy conversion device (ECD). Consequently, it is the ECD where the tribology problems arise in the green ship. Compared with the terrestrial environment, the



Fig. 3 Green ships that utilize different kinds of new energies.

marine environment is severe, changeful, and corrosive. It results in a more complicated boundary condition and multi-factor influence in the tribology issues. Taking the ECD of the wave energy as an example, it shows that different kinds of frictional components are used to transform the irregular movement of the wave into a reciprocating and/or rotary motion, such as hinge joints, bearings, and matching parts of a piston. The research accomplished in marine environment has confirmed that some typical tribological features arise in these friction components, e.g., lubrication failure, overload, abrasive particle deposition, marine biofouling [10], cavitation, and friction abrasion. For the wind and solar energy, the tribological performance of moving surfaces contained in the corresponding ECD presents completely different characteristics.

3.1 Tribology problem of sail-auxiliary technology

Up to now, the sail-auxiliary technology that is applied in ships has more than 100 types, and the structure differentiation of the wind sail is remarkable. Some typical wind sails, as those shown in Fig. 4, can be further defined into four categories: (1) Sail wing, also known as airfoil sail, which is designed based on the principle of airfoil profile, including: rectangular sail wing, triangular sail wing (or Jib for short), walker, and sky sails; (2) drum sail, which applies

the “Magnus Effect” to generate the propulsive force; (3) integration of the principle of airfoil profile and Magnus effect, named as the rotor-wing combination; (4) turbine sail of suction type, which is developed from the theory of controlled boundary layer separation.

Figures 5 and 6 show two kinds of foldable sails operating processes, which are the foldable rigid sails and foldable lifting sails, designed by the New Energy Group of Wuhan University of Technology (WUT). The functions of furling, stretching, and angle adjustment are all included. On a long voyage, the changeable wind load acting on the sails and the rubbing wear arising from the contact surface between the articulated mechanisms and sail’s horizontal ribs are two factors that influence the surface friction coefficient and reduce the mechanical efficiency of the driving system. Various studies suggest that an automatic lubrication system should be applied to the linkage mechanism, for example, using the oil-cup pressure oiler of the straight-through type to circulate the lubrication across the hinges’ joints. The wind sail and mast may be destroyed by the corrosive seawater under a long-time exposure to the marine environment, which will definitely change the aerodynamic characteristics of the sail-auxiliary system. The corrosion-resistant material and antifriction and



Fig. 4 Various types of sail-auxiliary ships.

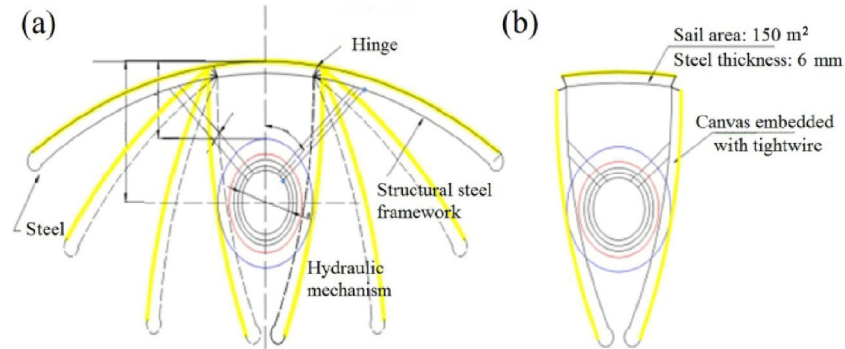


Fig. 5 Foldable rigid sail: (a) furling condition; (b) stretch condition.

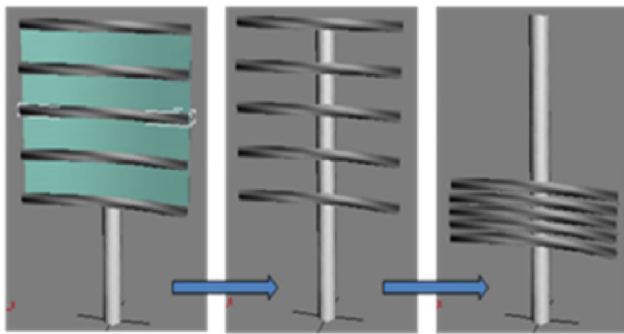


Fig. 6 Foldable lifting sails.

hard-wearing coating are two methods to prolong its service life. Directly acting on the mast through the wind sail, the time-varying wind force is transferred to the driving gear that is installed on the mast. This force load is the main factor that leads to the vibration and fretting wear of the components inside the driving gear. Three kinds of tribology problems should be taken into consideration, including the fatigue failure of bearing, wear, and agglutination of the gear tooth surface.

For operation security and port logistics, the marine ships are required to be operated at a fixed speed, about 80%–90% of full load, also called the economic speed. If the sail wing system is put into service, the main power system should be reduced to 40% or lower in order to keep the actual speed unchanged. However, keeping the crankshaft at a low speed for a long period is harmful for the combustion efficiency of a large marine low-speed diesel engine, because the emerging carbon deposits will lead to material degeneration on the piston surface, as shown in Fig. 7, and on the inner surface of the cylinder. Other problems, such as poor lubrication, resistance increase, and

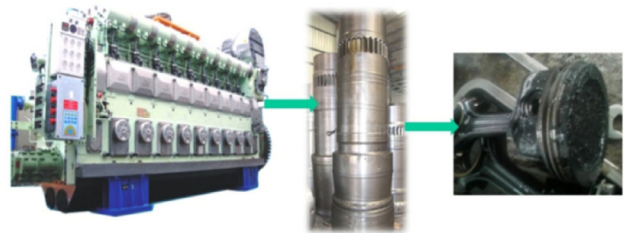


Fig. 7 Main engine, cylinder, and piston with carbon deposits.

cylinder wall scratching, are all unavoidable, and the worst condition is a broken-down engine. Therefore, the friction and wear characteristics of the moving surfaces located in the main engine components should be studied comprehensively, especially under the low-load working condition with the sail in use.

3.2 Tribology problem of solar photovoltaic system

The solar photovoltaic (PV) system is an approach for generating electrical power by converting the solar radiation into direct current electricity using semiconductors that utilize the photovoltaic effect. To realize the target of high energy-conversion efficiency, two methods of sun tracking (single and dual axis tracking) can be applied to a terrestrial PV system. As a comparison, various types of innovative structures are used to install the PV system on solar ships, as shown in Fig. 8. Especially, the form of “Solar Sailor” has been widely accepted and installed on catamarans [11], whereas the horizontal arrangement of solar panels is the best choice for small crafts or marine ships. Two reasons are considered: (1) Collection of as much solar radiation as possible under the limitation of deck area; (2) the increased weight coming from the solar panels, mounting bracket, and batteries

(if used) has a negative influence on the vessel’s metacentric height. Moreover, the structure of the solar sailor may worsen this problem.

3.2.1 Friction and wear

The I–V characteristic of a solar cell is directly affected by meteorological factors, including solar radiation, temperature, and wind, while other factors such as gaseous pollutants, air dust (smoke and dust particles and salt particles), and rainfall, can influence the PV cell’s reliability in different ways [12–15]. Various studies have shown that the seawater is one of leading factors for electrochemical corrosion process on the cell’s surface, and the salt particles emerging during the evaporation process of seawater can change the surface morphology of the PV cell’s cover glass by friction and wear [16]. The results shown in Fig. 9 are the salt-water experiments by using synthetic seawater, set at four different concentrations. In each group,

the upper picture shows the solar cell that is covered with salt particles by evaporating the seawater and the lower one is the cell’s surface morphology when the salt particles are cleaned away by fresh water. Further study also shows that some black spots appear at the upper surface of the cover glasses, which result in the reduction of spectrum transmittance.

3.2.2 Vibration and fretting wear

The inverter is an electrical device that converts direct current (DC) to alternating current (AC). In the PV system installed in a ship, the hull and low frequency vibrations caused by the waves and rotating machinery, respectively, are the major factors that lead to vibration and fretting wear of the mechanical connection parts in the inverter. Besides, the performance characteristics of electronic components and switch devices running under a multifactor effect, such as corrosive spray and oil mist suffusing



Fig. 8 Various types of solar ship.

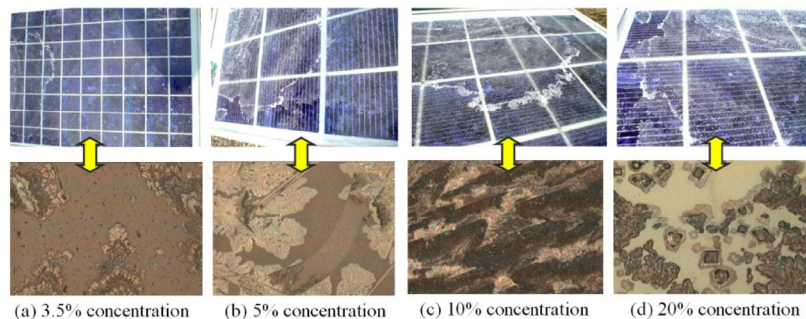


Fig. 9 Salt-water experiment of cell glass cover conducted under simulated marine environment.

in high temperature, also need to be paid comprehensive attention.

4 Tribological research for hull drag reduction

The hull resistance, which is composed by the frictional, stick pressure, and wave-making resistances, can be regarded as an acting force relating to the moving object in the fluid. Owing to the terminal conditions, including the viscosity and density of the fluid, surface roughness, and snit-fouling coating, the fluid boundary layer appears on the wetted surface of the hull, below the waterline. The longer the ship length is, the thicker the boundary layer becomes. All the kinetic and potential energy that the boundary layer acquires during the navigation comes from the hull. This physical effect of energy exchange is also the frictional resistance, which is the major of the three components of hull resistance. It is claimed that the proportion of frictional resistance in the hull resistance is up to 70%–80% [17], especially for the low-speed and medium-speed vessels. Numerous approaches aiming at the reduction of the frictional resistance of the green ship have been researched, including bionic materials and air bubble lubrication technology.

4.1 Hull surface roughness and biomimetic surface

The seawater fouling and corrosion, shown in Figs. 10 and 11, respectively, are the two factors that change the hull surface roughness, even after a short period of voyage. The direct results of the deterioration on the hull surface are that the route speed is reduced by 1–1.5 knots, while the energy consumption of the ship is kept at the same level as before. Under the worst situation, this reduction can reach 2 knots. Nevertheless, the idea that the resistance of a smooth surface is lower than that of a rough plane was widely accepted till the mid-1960s, when experiments showed that it is credible only under the constrain condition of low-speed fluid. On a smooth surface with high-speed fluid flowing over, the distribution of the velocity and pressure fields is more uneven than that with low-speed fluid. The momentum interaction of the turbulent boundary layer on the contact surface leads



Fig. 10 Fouling and corrosion on the hull surface.



Fig. 11 Bio-fouling.

to an obvious increase in hydraulic resistance. Thus, there is a dilemma.

Effective approaches from ship antifouling to drag reduction have been explored in depth, based on the innovative tribology theory that involves biological, conductive, alkaline, and bio-enzyme antifouling, the technology of low surface energy [18], chemical and structural bionics, etc. The antifouling coating containing organic tin and cuprous oxide (both toxic) has proved to be harmful to the marine environment and ecological system. The bionic coating that applies the technologies of low surface energy and biological surface microstructure is more adapted and green for the marine environment. In order to reduce the skin friction of underwater vehicles, Dou et al. [19] developed a kind of binary structured surface based on Benard convection. The test conducted in the small and high-speed tunnel SKLT-1 of Tsinghua University has proved its remarkable effectiveness for drag reduction

performance. The study on bionics assumes that the structure of rib-like squama that covers the shark body effectively prevents the surface from being adhered by sea creatures, and especially, reduces the vibration owing to the fluid flowing at a high relative speed. After the process of abstraction, amplification, and simplification based on the real microstructure of the shark squama, the bionic shark skin made in laboratory can currently contribute to about 7% of drag reduction in a test subject [20–22]. Using the forming technology of biological replication, Han et al. [23] designed a kind of bionic shark skin and claimed that this structure can improve the ratio of drag reduction up to 24.6%. Bai et al. [24] discussed an ecological concept to restrain the adhesion of sea creatures for ship application. Figure 12 shows some representative research contents by Bai. The shell at the upper left of the photograph in Fig. 12(a) is real and the three-dimensional print at the upper right is its microstructure. The data are measured by Phase Shift Micro XAM-3D, as presented in Fig. 12(b). In comparison, the shell at the bottom left is an artificial shell together with the three-dimensional print of its microstructure on the bottom right. The comparison of the three-dimensional prints in Samples 1 and 2 illustrates that this modeling technology can be applied to the hull surface when the most appropriate shell structure is selected.

4.2 Application of micro-bubble drag reduction

At the end of the 19th century, W. Froude established the assumption that the hull resistance could be reduced by injecting air into the fluid layer between the ship bottom and water, and the basic model is shown in Fig. 13. The initial experimental result was not as ideal as expected owing to the limited theoretical research and experimental conditions, but this innovation concept was regarded as the beginning for further research. In 1984, the American scholar Madavan [25] analyzed the micro-bubble drag reduction of solid revolution and claimed that the frictional resistance can be cut down by 50%–80%, which also proved the correctness of the research conclusion stated by Migirenk (USSR) [26]. The result also showed that: (1) For the ship operating at the same speed, the more air bubble ACS is injected, the lower the frictional

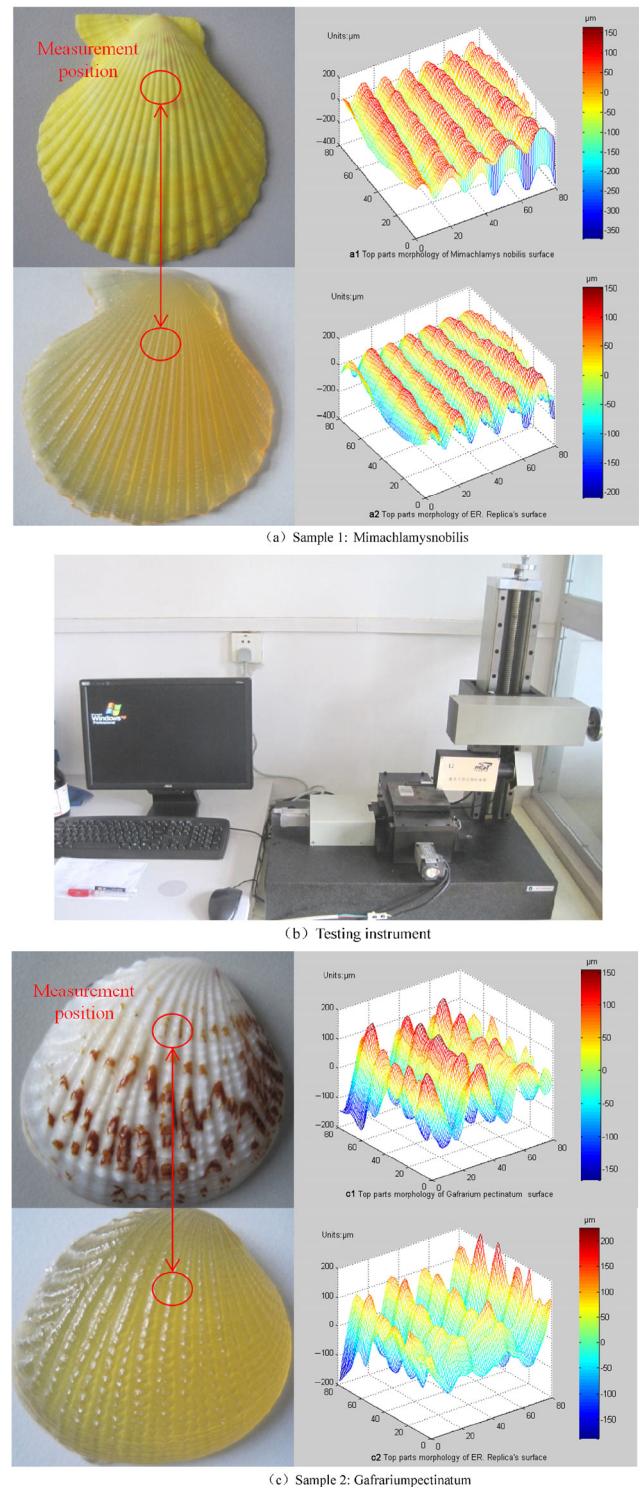


Fig. 12 The shell and its artificial model with microstructure respectively in comparison.

resistance becomes; however, the frictional resistance between the hull surface and water remains unchanged when it reaches a critical value, no matter how much air is subsequently charged. (2) The effect of drag

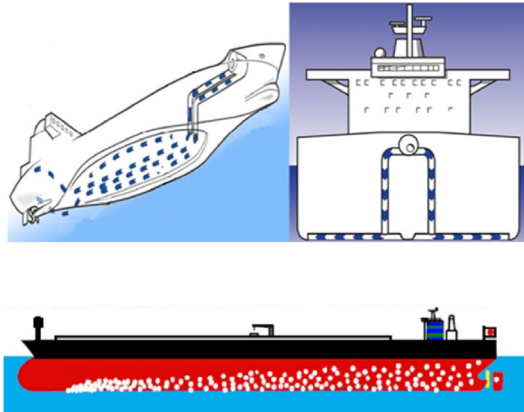


Fig. 13 Principle of Air Cavity System, ACS.

reduction decreases along with the increase in ship's speed, if the same volume of air bubble is injected. (3) The air bubble can hardly influence the flow resistance characteristics at the upstream region that is located in the front of the air nozzle, as well as the velocity distribution of the mixed media.

A case study on the 116-m training ship SEIUN-MARU installed with ACS claimed that a 5% (maximum) reduction of skin friction and 2% of net energy saving (NES) was obtained in 2001. Later, the full-scale test conducted on the Pacific Seagull confirmed 5% of NES [7]. However, some reports seem to have a conflicting opinion, explaining that the ACS leads to an increase of 1%–2% in the hull resistance and propulsion efficiency at model scale and about 0.6% of net power reduction at full scale. In China, the study on the micro-bubble drag reduction began in the 1980s, but the progress in research is remarkable. Dong et al. [27] studied the micro-bubble for both the plate and planing craft. Four factors are discussed in detail, including air velocity, volume, ejecting mode, and size of the air nozzle.

5 Tribological research for energy efficiency enhancement

The energy efficiency is one of main factors in the evaluation system of a green ship, i.e., to accomplish the maximization of output power when the same amount of energy resource is consumed during navigation. According to the new explanation certificated by IMO, as mentioned above, two correlative aspects EEDI and SEEMP are taken as guidelines for

energy efficiency enhancement of the newly built ships and ships in operation, respectively. Aiming at the improvement of energy efficiency and reliability, the tribological research referring to the green ship is stated from two aspects, as follows.

5.1 The marine power plant

The marine power plant is the key component of ships, in which any failures would cause a critical accident that threatens their safety. Because the marine environment is complicated and severe, the dynamic movement of ships during voyages can be changed by the meteorological conditions, e.g., wind, storms, and ocean currents. The fluctuation range and type of dynamic movement can directly weaken the lubrication action in the mechanical components, aggravate mechanical wear, and finally affect the power characteristics and mechanical efficiency of the dynamic system [28, 29].

The cylinder lubrication is essential for the normal operation of the main engine, and it is indicated that about 26% of mechanical failures in 645 cases were caused by poor lubrication in the cylinders, while 92 cases (14%) were the result of a wrong method of lubrication. Aiming at developing methods to protect the cylinder liner of the main engine from excessive wear, Xiong [30] stated a maintenance strategy comprising four parts, namely cylinder oil, fuel injection rate, pretreatment, and cooling water. Under a simulated experiment condition, Han et al. [31, 32] studied the internal relationship between four operating parameters (load, speed, temperature, and running period) and two relevant parameters, mass loss and surface roughness, which are in connection with the assembly of cylinder liner and piston ring. For comparison, this assembly was also processed by a surface treatment to analyze its variation in tribological characteristics. Liu et al. [33] assumed that a kind of micro-geometrical structure had a great impact on the lubricating property of the oil layer between cylinder liner and piston ring. Processing the micro-geometrical structure of pits and slots at the liner's inner surface, they analyzed the vibration frequency of the cylinder liner and the distribution of lubricant under the working condition, and explained that this structure can appropriately improve the lubrication

capability while the diesel engine was operating at a high rotating speed.

5.2 The transmission system

The stern bearing is used to support the stern shaft that transmits the power from the main engine to the propeller. Compared with other mechanical parts, its working condition is harsh. The reason is that the hydrodynamic lubrication in the stern bearing can hardly be formed owing to uneven pressure distribution and mechanical vibration, especially under the overload condition.

From the China Shipbuilding Industry Corporation (CSIC), Wang [34] analyzed the correlation between friction coefficient and rotating speed by lubricating the stern tube bearing with water and oil respectively. Wang et al. [35] stressed the abnormal working condition of the mechanical end face seal caused by the integrated effect of seawater pressure and friction force. The method of overall contact coupling was used to deal with the steady-state analysis of temperature distribution related to the friction pair of the stern shaft sealing. The research work conducted by WUT is focused on the tribological properties of a water-lubricated stern tube bearing that operates in a simulation test bench, as shown in Fig. 14 [36, 37], in which five domains are contained: (1) The derivation and solution of Reynolds equation that take both the speed of lubricating water and obliquity of propeller axis into consideration; (2) the finite element simulation for fluid-structure coupling related to the shaft, bearing, and lubricant (water-lubricated); (3) the study on the inner flow field of the stem bearing and lubricating mechanism by CFD and numerical analysis; (4) the evaluation of the performance of the water lubricated stem bearing based on the experimental parameters, such as the pressure of water film, temperature, and friction coefficient; (5) the analysis of the reliability of the water lubricated stem tube bearing from two aspects, the wear and fatigue life. Besides, it is claimed that other tribological problems can be conducted for further studying on the transmission system, as follows: (1) The theoretical improvement in boundary lubrication, fluid hydrodynamic lubrication, and elastic fluid dynamic pressure for the water lubricated stem tube bearing; (2) the friction coefficient of bearing

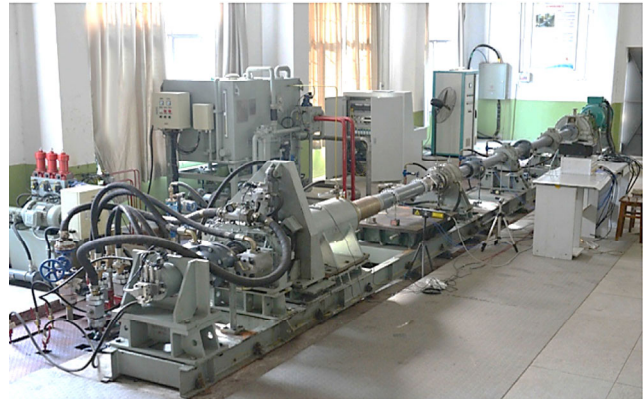


Fig. 14 Performance test platform for marine propulsion shafting system.

under the condition of different loads and linear velocities, and the lubricating property related to the size and gradient of the lubricating water channel; (3) the development of new materials that have the characteristics of low friction, wear resistance, self-lubrication, and high reliability.

6 Conclusions and prospects

For further development of the green ship, the tribological property analysis is one of the critical success factors, which implies the utilization of the tribology theory in the entire cycle of shipping industrialization, including design, manufacture, operation, and management (the four parts of the life cycle) for the purpose of energy conservation, environmental protection, and efficiency improvement. By setting the applicability, energy efficiency, and reliability of the green ship as the target for its future development, four domains should be further considered:

(1) Exploration of more extensive renewable energy technologies for application to the green ship.

(2) Improvement of the conversion efficiency (the primary energy) of the renewable energy system that is integrated in the green ship by exploring the friction and wear characteristics of the moving components in the mechanical system and the contact surfaces between the liquid-solid two-phases, especially taking the factors of marine environment into account.

(3) Application research on advanced materials to prolong the service life of rubbing pairs in the mechanical system, including low-carbon lubrication

materials, biomimetic materials, and antifouling coating.

(4) Research on the tribological problems of the traditional marine mechanical equipment, applicable to the green ship, from the viewpoint of EEDI and SEEMP improvement.

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