“WIND HUNTER“- THE ZERO EMISSION CARGO SHIP POWERED BY WIND AND HYDROGEN ENERGY

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SUMMARY

When a sailing ship with large rigid sails navigates in a sufficiently windy area, the thrusts from sails are strong enough to not only drive the ship at the proper speed but also rotate a large underwater turbine. The turbine generates electricity for the water electrolysis to generate hydrogen onboard. The hydrogen is attached to toluene and changed in the form of methyl-cyclo-hexane (MCH), which is in liquid form under ambient temperature and pressure. In the case of weak winds when the sails cannot generate sufficient thrust, the MCH is led to the dehydrogenation device. Using the hydrogen generated, the fuel cell supplies electricity to the electric motor propeller. Thus, the ship can navigate at a constant speed regardless of wind speed and direction. The concept of this ship is one of the best candidates for a Zero CO_2 emission ship, because it is operated by only wind energy.

NOMENCLATURE

L	Length (m)
B	Breadth (m)
D	Depth (m)
d	Draft (m)
Disp	Displacement (tf)
DW	Dead Weight (tf)
W	Wet Surface Area (m^2)
S	Sail Area Total (m^2)
Cx	Thrust Coefficient of Sail
Vw	Apparent Wind Speed (m/s)
T	Total Thrust of Sails (tf)
R	Total Resistance (tf)
Rh	Hull Resistance (tf)
Rtp	Turbine Resistance or Propeller Thrust (tf)
Fn	Froude Number
Vs	Ship Speed (kt)
Ct	Hull Resistance Coefficient
Dia	Diameter of Turbine/Propeller (m)
A	Circle Area of Turbine/Propeller (m^2)
Ptp	Power Output on Turbine or Propeller (kW)
Pgm	Power Output on Generator or Motor (kW)
H2	Hydrogen Generation or Consumption (m^3/day)
MCH	MCH Generation or Consumption (m^3/day)
ENDU	Days for Filling or Consuming MCH at Tank (day)
MCHT	MCH Storage Tank Capacity (m^3)
TOLT	Toluene Storage Tank Capacity (m^3)

1. INTRODUCTION

In order to realize the sustainable society, CO_2 emission from the activities of mankind needs to be reduced drastically.
Following the Paris Agreement in 2015, IMO (International Maritime Organization) adopted the resolution in April 2018 that all maritime voyages to emit zero CO_2 within this century, and to halve CO_2 emission by the year of 2050. This resolution will strongly accelerate the change of ship’s propulsion energy source from the fossil oil to zero emission energy source. The innovation of zero emission ship propulsion system needs to be researched and realized urgently.

2. CANDIDATES FOR ZERO EMISSION SHIP

Table 1 shows features of conventional ships and candidates for zero emission ships. And it also indicates their energy source, power generation device, propulsor device and remarks.

As for the nuclear ships, the practical technology has already been established and vastly applied in the naval ships and submarines. It is not so technically difficult to build nuclear cargo ships. However, the nuclear merchant ships are difficult to be introduced in the international shipping industry because of the negative opinions from the general public about the safety and nuclear disaster.
Regarding the CO2 recovery ships, the main part of ship propulsion system is the same as that of the conventional ships. However, the problems lie not only on the size of additional CO_2 recovery device, but also on the cost of transporting intruding discharged CO_2 to the storage site.
As for the battery-operated ships, even in the case of the most advanced lithium battery, the battery weight is quite heavy and it may not be suitable as the propulsion system for high-powered long-distance cargo ship.
Both fuel-cell ships and hydrogen engine ships are under development in maritime community. However, their technology is not yet so popular, because of the high cost of hydrogen related equipment.
Among the above candidate ships, it seems that the ships powered by wind as the main basis are one of the most suitable methods for the zero emission ships. Ocean winds have been utilized since the ancient times. Such sailing ships used to enjoy their golden era in the 19th century. However, because the wind speed and direction on the sea were not constant, it was impossible to keep the ships on time schedules. Since the industrial revolution, especially after the invention of steam turbine and diesel engine, steam turbine and diesel engine ships, which ran without wind, replaced wind powered sailing ships.
In this paper, we would like to propose “WIND HUNTER” which could be possible to run by both wing sails using wind energy and electric propellers using fuel cell with hydrogen energy. If the hydrogen is originated from a renewable energy source from wind energy, such ship is completely free from oil burning and CO_2 emission.

Table 1 Candidates for Zero Emission Ship

Kind of Ship	Energy Source	Power Generation	Propulsor	Remarks
Conventional	Oil, Gas	Diesel Engine	Propeller	Much CO2 Emission
Nuclear	Uranium	Steam Turbine	Propeller	Uranium Supply, No Public Acceptance
CO2 Recovery	Oil, Gas	Diesel Engine	Propeller	Needs of CO2 Recovery Plant
Battery	CO2 Free Electricity	Lithium Battery	E. Motor & Propeller	Small Capacity, Heavy Weight of Battery
Fuel Cell	CO2 Free Hydrogen	Fuel Cell	E. Motor & Propeller	CO2 Free Hydrogen Supply
Hydrogen Engine	CO2 Free Hydrogen	Hydrogen Gas Engine	Propeller	CO2 Free Hydrogen Supply, NOx Emission
Biofuel	Biofuel	Diesel Engine	Propeller	High-Cost Fuel, Pressure on Cultivated Land for Food
Wind powered	Ocean Wind	Wing Sail	Wing Sail	Few Thrust in Weak Wind

3. WIND CHALLENGER PROJECT

We have been developing the WIND CHALLENGER Project which is an extraordinarily large rigid wing sail for driving large merchant ship [1]. Fig.1 shows the concept of the WIND CHALLENGER sail. Its height can be changed from about 53m (Full sail) to about 23m (Reef Sail), breadth is about 15m, and maximum breadth of wing is about 3m. The shape of wing section is crescent type.
The telescopic massive steel spar which located inside the sails receives the various wind forces via enclosed rigid wing sail made of GFRP. This sail can be rotated by a pinion gear automatically to keep the proper angle which derive the maximum thrust for the ship.
In case of stormy and windy weather, the reefing is done automatically by the hydraulic cylinders inside of the spars depending on the stress of root part of the spar.
Fig.2 shows the sea trial photo of first WIND CHALLENGER Ship. Mitsui O.S.K. Line’s bulk carrier “SHOFU MARU” which was delivered on Oct. 7th 2022, from Oshima Shipbuilding Co., Ltd. She is 100 kDW bulk carrier fitted with one WIND CHALLENGER Sail in the forecastle deck.
The advantage of WIND CHALLENGER sail is the big change in the height and the area between full and reef sail, compared with traditional sails. Therefore, we can install larger sail than before and get stronger thrust. Table 2 shows the principal particulars of “SHOFU MARU”.
Fig.3 shows the example of the performance of energy saving ratio in various wind speed and direction at the ship speed of 14.3 knots based on the calculation at the stage of development of WIND CHALLENGER Project in 2015. In the case of TWS (True Wind Speed) 15 knots and TWA (True Wind Angle) 85 degrees, the fuel saving ratio was estimated about 9% according to our CFD calculation. Some zig-zag line in Fig.3 means the step of reefing, i.e., trigger for reefing operation is activated by the value of the moment which is sensed at the root of spar. Specifically, the energy saving

ratio for “SHOFU MARU” per WIND CHALLENGER sail is estimated to be about 5% on Japan-Australia east coast round-trip and about 8% on Japan-North America west coast round-trip at present.

Fig.1 WIND CHALLENGER Sail

Fig.2 “SHOFU MARU” at Sea Trial

Table 2 Main Particulars of “SHOFU MARU”

Item	Value	Remarks
Length	235.00 m	Over All
Breadth	43.00 m	
Depth	20.05 m	
Design draft	12.80 m	Moulded
Gross Tonnage	58,209	
Dead Weight	100,422 ton	Scantling
Main Engine	MITSUI MAN B&W 6S60ME-C10.5-EGRBP	
Ship Speed	14.3 knot	85%MCO, 15%SM, Design draft
Sail Area	abt. 700m2	Telescopic Rigid Sail

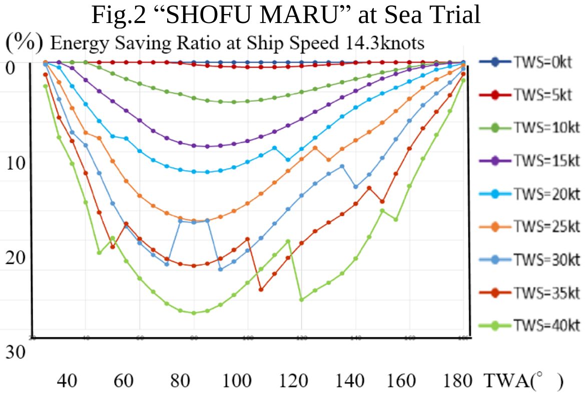


Fig.3 Example of Energy Saving Ratio Calculated in 2015

4. WIND HUNTER PROJECT

Fig.4 shows schematic drawing for the various forces acting on zero emission sailing ship, which is WIND HUNTER PROJECT. Difference between WIND HUNTER PROJECT and WIND CHALLENGER PROJECT is while wind assists main engine propulsion for fuel saving, propulsion and energy only comes from wind and achieve zero emission for WIND HUNTER.

To keep the constant ship speed, the resistance of hull (Rh) has some constant value, however at the weak wind, the ship thrust (T) is smaller than (Rh), so that the propeller thrust (Rtp) is needed. In case of strong wind, the turbine resistance (Rtp) generates excessive power [2].

Fig.5 shows the schematic drawing of main components and energy flow for WIND HUNTER which has mainly two major remarkable modes. One is the production and stowing of the hydrogen, which is done by the water turbine generator, the water electrolyser and the hydrogeneration device in the case of strong wind. The other is consumption of the hydrogen by activating the dehydrogenation device, the fuel cell and the electric motor driven propeller in the case of weak or no wind.

To achieve zero emission for WIND HUNTER, an acquisition of large amount of wind energy is important. The size and performance of WIND CHALLENGER Sail has the potential to run the ship at the cruising speed and generate proper amount of hydrogen which is made from kinetic energy of the wind via electricity. The volume of hydrogen gas is too large to store onboard the ship, therefore, it is necessary to change hydrogen gas into other hydrogen carriers such as liquid hydrogen, compressed gas hydrogen, Methyl-Cyclo-Hexane (MCH), ammonia, metal hydride, etc. For this research, a chemical hydride MCH/Toluene system shown in Fig.6 is chosen from the viewpoint of safety, economy and handling. MCH which is made from Toluene and hydrogen with the catalyst is one of the excellent hydrogen carriers, because its shrinkage rate from hydrogen gas to MCH liquid is approximately 1/500 in the condition of ambient temperature and pressure.

As for the electric generator and motor propeller, we propose the common usage to simplify both components together in the system.

Fig.5 shows a summary for the concept and energy flow of the WIND HUNTER which has two modes for propulsive operation:

1) In the case of strong wind: Red line. The excessive energy, which is produced more than the energy needed for ship's cruising speed, generates electricity, then activates the electrolysis device and produces hydrogen gas. The hydrogeneration device enables hydrogen gas to be attached to toluene and makes MCH to act as the hydrogen carrier and stores it in the MCH tank
2) In the case of a weak or no wind: Blue-dot line. The energy is less than the energy needed for ship's cruising speed and electric driven propeller rotates with electrics via fuel cell, i.e., fuel cell is driven by the hydrogen gas which is separated from MCH stowed in the MCH tank using the dehydrogenation device.

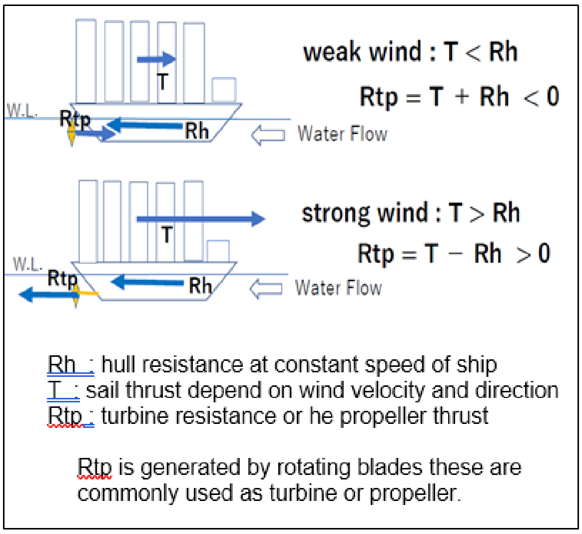


Fig.4 Forces Acting on Zero Emission Sailing Ship

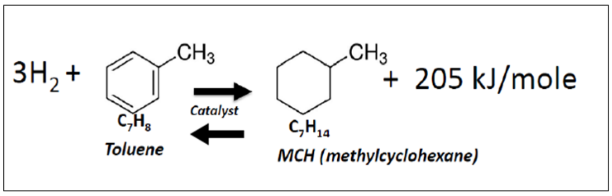


Fig.6 Chemical Hydride System

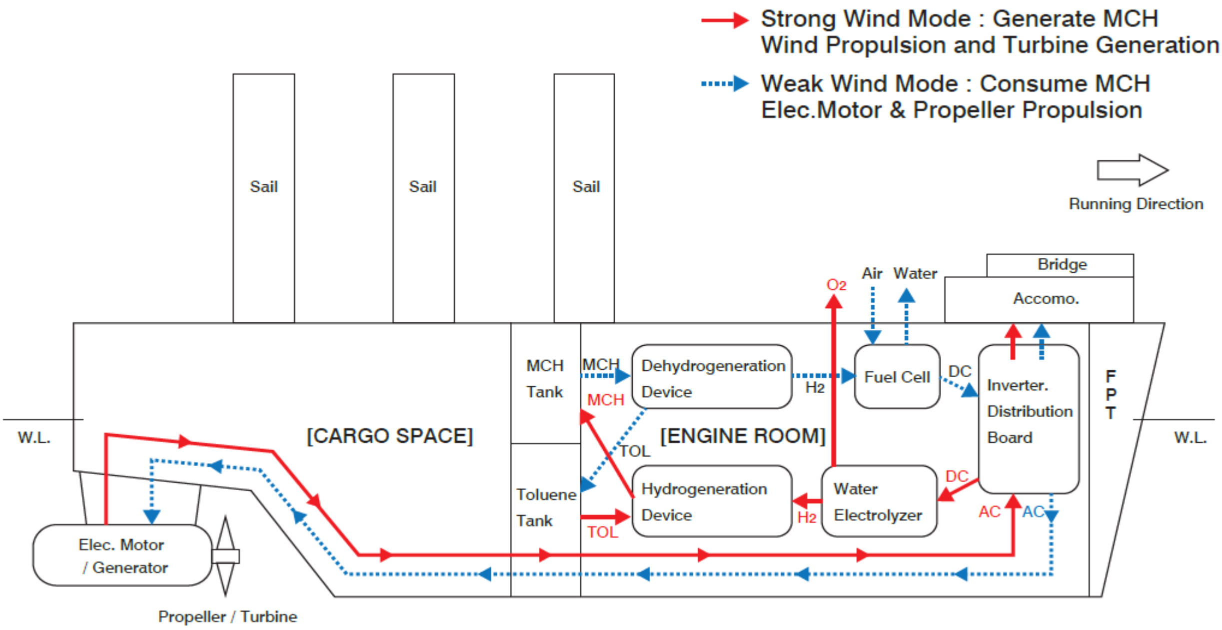
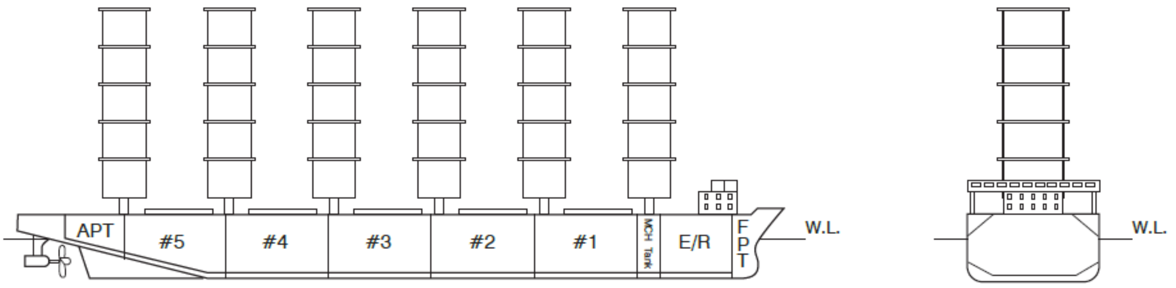


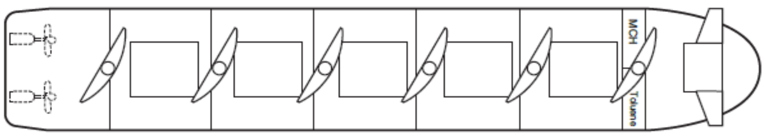
Fig.5 Main Components and Energy Flow of the WIND HUNTER

5. ARRANGEMENT AND PARTICULARS

Fig.7 shows and is proposed the rough arrangement and main particulars for 220m length Bulk Carrier type Zero Emission Sailing ship [3]. The bridge is to be in the fore part of the ship to keep forward visibility. The accommodation and engine room are also in the fore part or near by the bridge for the convenience of operation of the ship.
The hull form is so called Buttock Flow type with large skeg in the ship's centre line. This hull form avoids the speed reduction by the hull wake at the point where the turbine/propeller are fitted, and the skeg keeps the course stability.

Two pod type turbine/propellers with generator/motors are installed in parallel at the end of the hull to acquire or give the kinetic energy of water flow.
Six sails are installed on the ship centre line at every hatch end space.





L x B x D:	220m x 36m x 20m
d:	13m
DW:	75,500tf
Sail:	(80mx22mx6) 10,500m^2
Ship Speed:	Average 12knots
Fuel Cell:	4,000kW
Turbine/Propeller (Pod):	9.6mΦ x 2
MCH/Toluene Tank:	1,000m^3 each

Fig.7 Rough General Arrangement and Main Particulars

6. CASE STUDY FOR PERFORMANCE

A case study for performance of the WIND HUNTER is carried out in various cases of wind velocity and ship speed. Table 3 shows the summary table for the various performance factor and estimation results for 75kDW Bulk Carrier mentioned in Section 5 and Fig7. The definition and explanation of each symbol is shown in the column of Term & Remarks. Here, the total area of sails is about 10,500m^2, and the diameter of turbine/propeller (Dia) is about 9.6m

6.1 STRONG WIND CASE

Regarding the strong wind case which is explained in the red line in Fig.5, ‘Strong Wind‘ column in table 3 shows the estimation for hydrogen generation capacity and related data. In this case, the apparent wind velocity (Vw) 15m/s drives the ship not only at the speed (Vs) 14knots but also generate the electric power (Ptp) about 10MW using the turbine generator. This electricity is converted to hydrogen gas (H2) about 50Mm^3 by the water electrolyser whose conversion ratio is assumed 5kWh/m^3. The hydrogeneration device makes the MCH about 100m^3/day using the hydrogen gas and toluene with catalyst. Here, the shrinking rate of hydrogen gas to MCH is assumed 1/500. The MCH tank capacity (MCHT) is 1,000m^3, therefore the endurance (ENDU) to full up the tank is about 10 days.

6.2 WEAK WIND CASE

Regarding the weak wind case which is explained in the blue dot line in Fig.5, ‘Weak Wind‘ column in table 3 shows the estimation for hydrogen consumption capacity and related data. In the extreme condition of apparent wind velocity (Vw) 0m/s, the propellers are required to emit the power (Ptp) about 2.2MW and the fuel cell to emit the power (Pgm) about 2.8MW for driving ship speed of 10knots, here, the propeller efficiency is assumed 0.78. The MCH about 100 m3/day equivalent to the hydrogen (H2) about 50Mm3/day is consumed and this hydrogen is changed to the electricity by the fuel cell whose conversion ratio of 1.35kWh/m3. Therefore, the endurance of voyage using the fuel cell (ENDU) is about 10 days in case of ship speed 10knots.

6.3 MARGINALWIND CASE

The marginal wind is the special wind velocity at the condition; Rtp = 0, T = Rh, shown in Fig.4 and Table 3. The ship neither generates nor consumes hydrogen in case of above condition. ‘Marginal Wind‘ column in table 3 shows the wind velocity 6.5m/s is the sufficient wind velocity of ship speed 12knots, and the endurance (ENDU) at this condition is unlimited.

6.4 VOYAGE PLAN

For operating such kind of ship, it is important to keep the balance of the generation and consumption for maintaining punctual service. The voyage plan should be organized taking keen consideration on the wind and climate forecasting, voyage route, MCH reserve capacity and cruising speed [4].
For example, for 14 days voyage, if the ship has two no wind (Vw: 0m/s, Vs: 10knots) days, ten marginal wind (Vw: 6.5m/s, Vs: 12knots) days and two strong wind (Vw: 15m/s, Vs: 14knots) days, average cruising speed is 12knots and MCH consumption (about 200m3) is same as MCH generation. Thus, many various patterns of voyage plan are considered to meet specific voyages.

Table 3 Performance Estimation of WIND HUNTER

Symbol	Unit	No Wind	Marginal Wind	Strong Wind	Term & Remarks
L	m	220.0	220.0	220.0	Length
B	m	36.0	36.0	36.0	Breadth
D	m	19.5	19.5	19.5	Depth
d	m	13.0	13.0	13.0	Draft
Disp	tf	85,457	85,457	85,457	Cb:0..83, Buttock Flow Hull Form
DW	tf	75,457	75,457	75,457	Dead Weight (LW:10,000tf)
W	m2	12,276	12,276	12,276	Wet Surface Area
S	m2	10,560	10,560	10,560	Sail Area Total (H80mxB22mx6sets)
Cx		1.9	1.9	1.9	Thrust Coeffecient of Sail
Vw	m/s	0.0	6.5	15.0	Apparent Wind Speed (Cross Wind)
T	tf	0	54	282	Total Thrust of Sails: T=R
R	tf	0	54	282	Total Resistance: R=Rh+Rtp
Rh	tf	37	54	73	Hull Resistance
Rtp	tf	-37	0	208	Turbine Resisance or PropellerThrust
Vs	kt	10.0	12.0	14.0	Ship Speed
Fn		0.116	0.140	0.163	Froude Number : Vs/(gL)^0.5
Ct		0.0022	0.0022	0.0022	Hull Resistance Coeffecient
Dia	m	9.6	0.0	9.6	Diameter of Turbine/Propeller
A	m2	145	0	145	Sircle Area of 2 Turbine/Propeller
Ptp	kW	2,179	0	11,081	Power Output on Turbine or Propeller
Pgm	kW	2,794	0	10,306	Power Output on Generator or Motor
H2	m3/d	49,663	0	49,467	Hydrogen Generation or Consumption
MCH	m3/d	99	0.0	99	MCH Geneneration or Consumption
ENDU	day	10.1	∞	10.1	Days for Filling or Consuming MCH at Tank
MCHT	m3	1,000	1,000	1,000	MCH Storerage Tank Capacity
TOLT	m3	1,000	1,000	1,000	Toluene Storage Tank Capacity
Remarks		Thrust by Propeller	Thrust by Sail	Thrust by Sail-Turbine	

7. SUBJECT FOR FUTURE DISCUSSION

Following is the agenda for the future discussion towards the realization of the WIND HUNTER as a large size cargo ship.

・Selection of a hydrogen carrier

Chemical hydride (Toluene/MCH) is being used here, but other carriers such as liquid hydrogen, pressurized hydrogen, ammonia hydrogen absorbing alloy can also be considered. A discussion to compare in terms of safety, cost, handling and business opportunities is required

・Weight reduction of WIND CHALLENGER Sails

To enable increasing the area and height of WIND CHALLENGER Sail, further development of lighter and stronger material such as CFRP for moving spars inside of the wing sail will be needed instead of steel spars.

・Common usage of Generator/Motor and Turbine/Propeller

The ship uses MCH production mode in the strong wind area, and MCH consumption mode in the weak wind area. Therefore, the turbine/propeller device is used as energy collector in strong wind, and the energy emitter in the weak wind. The research on the optimum blade shape of the device will be required.

・Customizing the fuel-cell specification

Development of the fuel-cell to meet the power demand of the two-mode operation will be needed.

・Integral usage of heat energy

Heat energy which is absorbed in or emitted from components such as fuel cell, water electrolyser, hydrogeneration and de-hydrogeneration should be researched and be used properly.

・Voyage plans and selection of voyage routes

Development of the voyage programs is necessary considering the punctuality of voyage schedules, the weather forecast, ship cruising speed, and safety [4].

8. CONCLUSION

We propose WIND HUNTER as a Zero CO_2 Emission ship abiding by the resolution of 2018 IMO meeting. The total energy for the WIND HUNTER is supplied by the ocean wind and WIND HUNTER has two modes of operations: the energy collection mode in the strong wind; and the energy consumption mode in the weak wind. The generator turbine (commonly used with electric propellers), water electrolyser, and hydrogeneration device will be used to collect energy. The de-hydrogeneration device, fuel cell, and electric motor (commonly used with generator turbines) will be used to emit energy.

The performance study on a 75kDW Bulk Carrier is carried out at the various assumption of wind velocity, ship speed, hydrogen and MCH storage capacity. And we propose that this concept of ship is suiting to the forthcoming hydrogen society as one of the solutions for zero emission society.

Technologies of the above components has basically already been established either in land or marine fields. The WIND HUNTER will be one of the most promising technologies for the next generation merchant ships, and the acceleration of its research and development will be expected.

In addition to zero emission cargo carrier, it is also now under investigation to create hydrogen production vessel, i.e., the vessel sails out from port with full of Toluene. Then, the vessel goes to windy area, produce hydrogen and store as MCH onboard. Once tanks are filled up enough, the vessel comes back to port for discharging MCH for shore usage.

9. REFERENCES

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