Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2019, 59 (131), 9–15
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/346

Received: *06.09.2019*
Accepted: *16.09.2019*
Published: *30.09.2019*

Improving the efficiency of a gas-fueled ship power plant using a Waste Heat Recovery metal hydride system

Oleksandr Cherednichenko[1]✉, Mykhaylo Tkach[2], Boris Timoshevskiy[3]
Valerii Havrysh[4], Serhii Dotsenko[5]

[1,2,3] Admiral Makarov National University of Shipbuilding
9 Heroiv Ukraine Ave., 54025, Mykolayiv, Ukraine
[1] Operation of Ship's Power Plants and Heat Power Department
e-mail: cherednichenko.aleksandr65@gmail.com
[2] Department of Engineering Mechanics and Mechanical Technology
e-mail: mykhaylo.tkach@gmail.com
[3] Department of Internal Combustion Engines, Plants and Technical Exploitation
e-mail: borys.tymoshevskyy@gmail.com
[4] Mykolayiv National Agrarian University
Department of Tractors and Agricultural Machinery, Operating and Maintenance
9 Georgiy Gongadze St., 54020 Mykolayiv, Ukraine, e-mail: havryshvi@mnau.edu.ua
[5] Admiral Makarov National University of Shipbuilding, Pervomaisk Polytechnic Institute
109 Odeska St., 55202 Pervomaisk, Mykolayiv region, Ukraine, e-mail: admin@ppi.net.ua
✉ corresponding author

Key words: waste heat recovery, low-speed engine, metal-hydride, hydrogen, LNG-powered ship, total waste heat utilization factor

Abstract

Due to environmental, energy, and operating cost constraints, the number of liquefied natural gas (LNG)–powered ships is increasing. To avoid decreasing the thermal efficiency of two-stroke, low-speed diesel engines, high-pressure gas injection is used. The specific energy consumption of a gas fuel compressor is around 0.35 kWh/kg, which has a negative impact on the efficiency of ship power plants. To reduce the primary energy consumption of a gas fuel supply system, waste heat recovery (WHR) technologies may be used. This study investigated whether WHR metal hydride technology was suitable for improving the efficiency of low-grade heat waste in marine diesel engines. The key factors of this technology were revealed, and the design scheme was described. Working fluids were also analyzed, and a mathematical model of a WHR metal hydride plant was developed, and the results were represented. The calculations showed that the above technology could increase the operating power of a propulsion plant by 5.7–6.2%. The results demonstrate the possibility of applying WHR metal hydride equipment for gas fuel compressor drives in LNG-powered ships. The novelty of this study lies in the investigation of metal hydride technology for application in the waste heat recovery systems of LNG-powered ships.

Introduction

Since ancient times, mankind has transported cargo by water, which remains an essential component of human civilization. Sea transportation is currently an integral part of the global transport system, and according to UNCTAD, about 90% of the world's freight shipments are transported by sea (UNCTAD, 2017), primarily because of the lower energy costs of maritime transport compared with land and air transportation (Chapman, 1989).

Monitoring greenhouse gas emissions to prevent climate change has become one of the main trends in the development of ship power plants. According to the forecasts of the International Maritime Organization (IMO), without greenhouse gas emission control, carbon dioxide emissions may double by 2050 compared with 2012 (IMO, 2016). In this context, IMO regulations strictly require increased energy efficiency.

In accordance with the requirements of the IMO resolutions for each new vessel with 400 gross tonnage and above, it is necessary to determine the Energy Efficiency Design Index (EEDI) (IMO, 2016):

$$\mathrm{EEDI} = \frac{\mathrm{CO_2 emission}}{\mathrm{Transport\_work}} = \frac{\mathrm{Engine\ power} \cdot \mathrm{SFC} \cdot \mathrm{C_F}}{\mathrm{DWT} \cdot \mathrm{speed}} \quad \mathrm{gCO_2/(ton \cdot mile)} \tag{1}$$

CO_2 emissions can be lowered by reducing specific fuel consumption and/or using low-carbon fuels. Due to environmental concerns and energy issues, the use of natural gas as a marine fuel has been heavily investigated because it is one of the cleanest hydrocarbon fossil fuels (Grljušić, Medica & Radica, 2015). Therefore, LPG-powered ships are promising alternatives for complying with ship emissions regulations established by the IMO (Geertsma et al, 2017).

The use of liquefied natural gas (LNG) as a marine fuel reduces the carbon factor by 12% compared with heavy fuel oil (HFO). In addition, the lower heating value of LNG (around 50 MJ/kg) is higher than petroleum fuels, which reduces the specific fuel consumption (SFC) of diesel engines by 14%. Moreover, energy cost of LNG is lower than petroleum fuels. In August 2019, the global average bunker prices were USD/t: IFO180 – 475; MGO – 688.5 (Ship&Bunker, 2019) which correspond to energy costs of USD/GJ: IFO180 – 11.88; MGO – 16.20. These values are higher than the energy cost of LNG (7.56–7.98) (Gonzales, 2019). Due to ecological regulations and lower fuel costs, there has been an increase in the number of LNG-powered ships. The gaseous fuel substitutes from 92 to 97% of conventional fuel at full load (MAN Diesel & Turbo, 2009). To ensure the operation of an engine without decreasing its efficiency, the required gaseous fuel delivery pressures range from 15 to 30 MPa, which depends on the engine load (MAN Diesel & Turbo, 2014a). The specific power consumption of a high-pressure gas fuel compressor is around 0.35 kWh/kg (MAN Diesel & Turbo, 2017), which worsens the efficiency of a ship propulsion plant. To reduce its energy consumption and, therefore, operation costs, waste heat recovery systems may be used to drive these compressors.

Low-speed diesel engines with efficiencies around 50% are widely used in ship power plants. The rest of the fuel energy is lost, so the use of waste heat recovery systems is the solution to improving the efficiency of marine propulsion engines. The heat recovery systems can be classified according to further applications of energy obtained (Kalinichenko, Havrysh & Hruban, 2018): 1) mechanical work (to drive mechanical devices); 2) electricity generation; and 3) heating and cooling generation. High-pressure gas fuel compressors require either mechanical or electric drives.

The waste heat of low-speed diesel engines has a low-grade heat potential, so the temperature of the exhaust gases does not exceed 520 K (MAN energy solutions, 2019). Under such conditions, traditional heat recovery systems are not efficient enough, which has prompted researchers to seek new technologies. Thermoelectric generators and metal hydride systems are alternatives, but they have low efficiencies and are expensive (Arsie et al, 2015). The use of metal hydride systems may be more efficient under the above conditions.

In recent decades, the use of hydrogen as an energy carrier has received great attention. Metal hydride systems can be used to convert waste energy into useful energy to power cooling machines, heat pumps, and mechanical drives (Miled et al, 2017). Therefore, great attention has been paid to waste heat recovery metal hydride systems for ship power plants. Metal hydride units that continuously operate are based on the ability of a number of substances – metal hydrides – to reversibly absorb and release hydrogen. At the same time, the increase in the temperature of the metal hydride leads to an increase in the pressure of the emitted hydrogen (Broom, 2011). This gives the opportunity to create metal hydride heat energized cyclic hydrogen compressors (Lototskyy, 2014). The use of a metal hydride slurry as a working fluid in a chemically inert liquid (Snigder, Versteeg & van Swaaij, 1993) made it possible to create metal hydride compressors (James et al., 2016), storage, and transportation systems (Brown, McClaine & Bowen, 2016) operating in a continuous cycle. However, the studies for WHR systems based on metal hydride technologies for LNG-powered ships have not yet been reported, so it is important to study the above system to reduce primary energy consumption. Therefore, the purpose of this study focuses on increasing the energy efficiency of a high-pressure fuel gas compressor using a waste heat recovery metal hydride plant. This study is based on previous publications carried out by scientists at the Admiral Makarov National University of Shipbuilding (Tkach et al, 2014; 2015).

Methodology

Subsystems of the marine propulsion plant

The modeling of processes in the marine propulsion units based on a dual-fuel low-speed diesel engine with a waste-heat loop requires the development of a structural diagram. The integrated diagram can be represented as a system of three functionally interconnected subsystems such as:

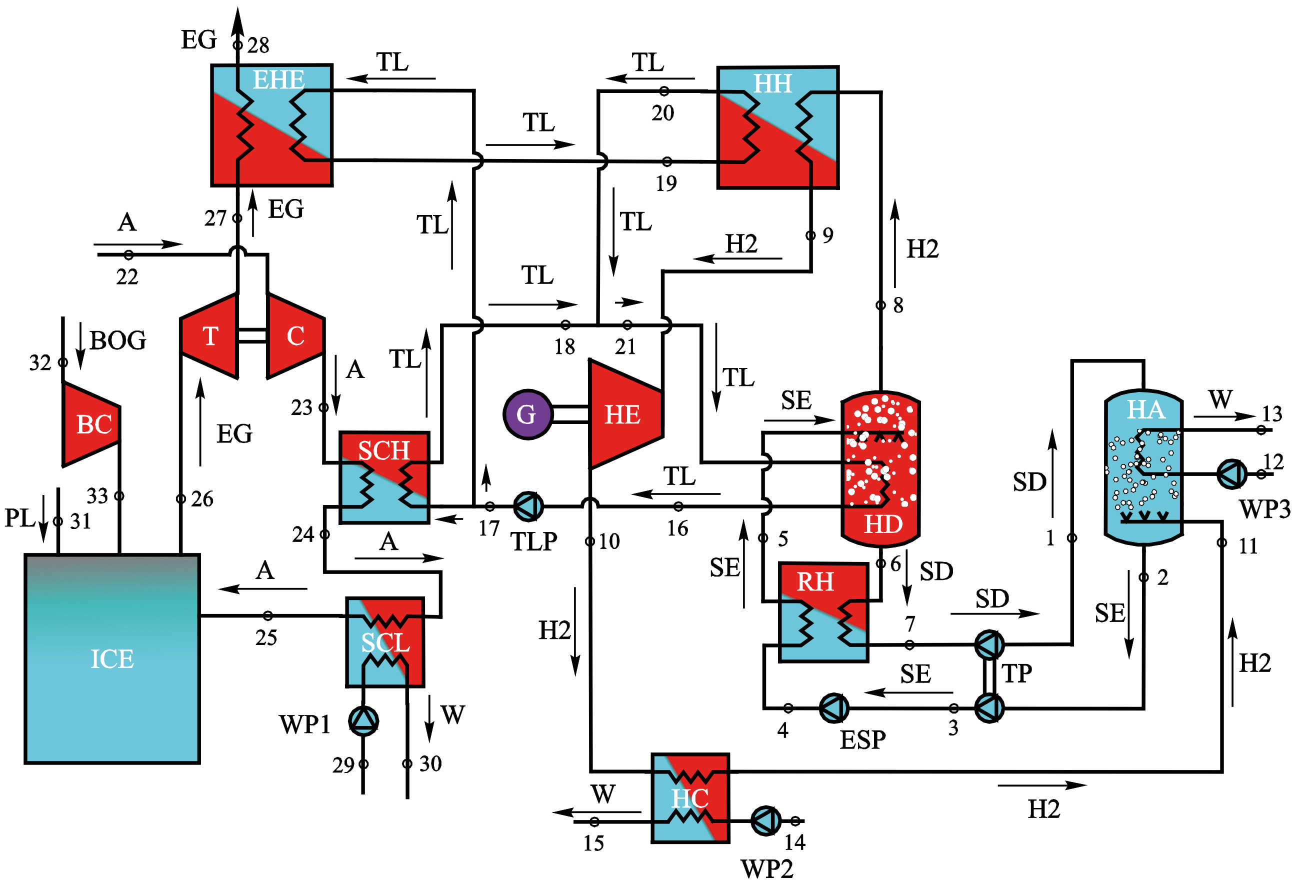
- energy subsystem (conversion of fuel energy into mechanical, electrical, or thermal energy);
- heat recovery subsystems (conversion of the waste heat into mechanical, electrical, or thermal energy);
- subsystem for the treatment and supply of gas fuel.

Subsystem elements are connected by the flows of energy carriers (thermal liquid and working fluids of cycles), by means of which the processes of energy interaction between the subsystems and, in general, the power unit are carried out. Technological parameters of working mediums such as pressure, temperature, and flow rate are the main parameters of the mathematical model of any energy subsystem.

Description of the System

In the WHR metal hydride units under study, the intermediate thermal liquid (TL) transfers heat from the exhaust gases (EG) of the diesel internal combustion engine (ICE) to a hydrogen desorber (HD) where high-pressure hydrogen is released from the enriched metal hydride slurry (SE) and then to the hydrogen heater (HH) (Figure 1).

Hydrogen released at high pressures enters the hydrogen expanding engine (HE), where its pressure decreases. At the same time, the potential energy of the hydrogen flow is converted into mechanical work. Next, low-pressure hydrogen enters the hydrogen gas cooler (HC) and the hydrogen absorber (HA). The depleted hydride slurry (SD), formed in the desorber, also enters the hydrogen absorber (HA), making it possible for the hydrogen absorber (HA) to absorb hydrogen at low pressure and temperature and obtain enriched hydride slurry (SE). The transfer of the enriched hydride slurry (SE) from



The numbers of control points (1 … 33) corresponding to the temperatures (T_1 … T_{33}), pressures (P_1 … P_{33}), enthalpies (h_1 … h_{33}), and heat flows (e.g., $Q_{1\text{-}2}$) considered in the text below.

Figure 1. The physical structure of the waste heat recovery metal hydride unit

the absorber to the desorber is carried out by the enriched hydride slurry pump (ESP). Reducing the power of this pump is achieved using a turbo-pump (TP), which uses mechanical energy to reduce the pressure of the enriched hydride slurry pump (ESP) to increase the pressure of the enriched hydride slurry (SE). Reducing the heat consumption for heating the enriched hydride slurry (SE) from the absorption temperature to the desorption temperature is achieved using a regenerative enriched hydride slurry heater (RH).

Simulation Model

The efficiency of the WHR metal hydride unit is equal to:

$$\eta_e = \frac{P_{HR}}{Q_{5-d} + Q_d + Q_{8-9}} \quad (2)$$

where P_{HR} is the useful mechanical power of WHR unit; $Q_{5\text{-}d}$ is the thermal power of heating the hydride slurry; Q_d is the thermal power needed for the desorption reaction; and $Q_{8\text{-}9}$ is the thermal power required for hydrogen overheating.

The useful mechanical power P_{HR} is determined as the difference between the mechanical power obtained in the hydrogen expanding engine P_{HE} and the power consumed by pumping the slurry P_{ESP}, and the thermal liquid of hot P_{TLP} and cold P_{WP2} + P_{WP3} loops:

$$P_{HR} = P_{HE} - P_{ESP} - P_{TLP} - P_{WP2} - P_{WP3} \quad (3)$$

The relative capacity of the unit is assumed as a criterion for the efficiency of a WHR metal hydride unit

$$PR = P_{HR} \cdot P^{-1}{}_{\text{shaft}} \quad (4)$$

where P_{shaft} is the main engine output shaft power, kW.

To approximately assess the main engine shaft power, the ship propulsion power was statistically estimated. For a LNG gas carrier, this expression is represented as (Giernalczyk, Górski & Kowalczyk, 2010):

$$P_{\text{shaft}} = (1.34571 + 0.00003091 \cdot Dn) \cdot V^3 \text{, kW} \quad (5)$$

where: Dn is the ship deadweight, t; and V is the speed of a ship, knot.

To estimate the proposed system, some technical indicators were used: exhaust gas energy utilization factor Ψ_g; the total waste heat utilization factor (Kalinichenko, Havrysh & Hruban, 2018); and the specific power of a waste heat recovery unit PHR, efficiency.

The exhaust gas energy utilization factor is calculated as:

$$\psi_g = (T_{\text{out}} - T_{at}) \cdot (T_{eg} - T_{at})^{-1} \quad (6)$$

where T_{eg} is the exhaust gas temperature, K; T_{at} is the ambient temperature, K; and T_{out} is the outlet temperature after WHR unit, K

The total waste heat utilization (recovery) factor is equal to:

$$\xi = P_{hr} \cdot \eta_e \cdot Pe^{-1} \cdot (1 - \eta_e)^{-1} \text{, kW/kW} \quad (7)$$

where P_{hr} is the power of the waste heat recovery unit, kW; and η_e is the efficiency of a diesel engine.

Results

Research was carried out for the propulsion plant of a Q-Max LNG carrier with a capacity of 250,000 m^3. When modelling the processes in the gas fuel supply subsystem, the following initial data was assumed: the pressure of the gas injected ranged from 25 to 30 MPa (MAN Diesel & Turbo, 2009), and the energy consumption of the fuel gas compressor was 2.8–3.0% of the engine power. According to the recommendation of MAN for a Q-Max LNG carrier with a capacity of 250,000 m^3 at a speed of 20 knots, the main diesel engine shaft power is 42.6 MW. According to the recommendation of MAN Diesel & Turbo, a dual-fuel, low-speed diesel engine 8G90ME-C10.5-GI was chosen. Its main characteristics are given in Table 1. Engine specifications were adopted in accordance with the limitations of IMO Tier II, and the share of pilot fuel was 3% (MDO according to ISO 8217).

Table 1. Engine Specifications 8G90ME-C10.5-GI to ISO 3046 / 1-2002 at 85% load

Parameter	Unit	Value
Specified continuous capacity	kW	42,600
Rate speed	min^{-1}	80
Brake mean effective pressure	bar	19.5
Supercharged pressure	bar	4.2
Specific gas fuel flow rate	g/kWh	135
Pilot fuel	%	3
Exhaust gases:		
flow rate	kg/s	93.5
temperature*	K	504

The exhaust gas temperature did not exceed 520 K. Due to the sulphur content in marine fuels, the exhaust gas temperature after waste heat recovery exchanger cannot be lower than 418 K (MAN Diesel & Turbo, 2014b). Therefore, the potential temperature drop of exhaust gases in the recovery heat exchanger ranged from 63 K to 103 K, and these low values complicate the development of WHR systems. Since LNG does not contain sulphur, it has a lower exhaust gas temperature after the heat exchanger in WHR systems, which increases its efficiency.

A simulation was carried out under the following environmental conditions: an air temperature T_a of 298 K, and a cooling water temperature T_{sw} of 298 K. The physical structure of the WHR metal hydride system was developed using the Aspen Plus system for modelling chemical and physical processes, and is presented in Figure 1. The developed mathematical model takes into account basic physical principles including material and heat balances, phase equilibrium, and heat and mass transfer processes.

This study focuses on the waste heat recovery from the charge air cooler and exhaust gases, whose share in the total thermal balance is 38.06%.

To simulate heat exchange processes, the energy consumption of pumping must be determined. So, geometrical characteristics of heat-exchange surfaces and hydraulic resistances of typical shell-and-tube heat exchangers were calculated using the parameters specified in the design scheme. Hydraulic resistances were 20 and 30 kPa on the cold and hot sides, respectively.

Table 2. The thermal power of heat exchangers

Parameter	Unit	Value
Exhaust Gas Heat Exchanger	MW	14.73
High Temperature Scavenge Air Cooler	MW	10.73
Hydrogen Heater	MW	2.23
Hydrogen Gas Cooler	MW	0.51
Hydrogen Desorber	MW	23.23
Hydrogen Absorber	MW	23.32
Regenerative Enriched Hydride Slurry Heater	MW	5.45

Therminol® 66 (a synthetic organic liquid with a maximum operating temperature of 345°C) was used as an intermediate coolant, and Slurry MmNi4.5Al0.5 in Therminol® 66 was used as the working fluid in the metal hydride circuit.

The main parameters of the working mediums in the cycle are presented in Table 3 (ISO conditions).

The relative capacity of the WHP metal-hydride unit was PR = 0.06.

The regeneration of mechanical energy was carried out by a hydraulic motor, which drives the metal hydride circuit booster pump and allows the unit to increase its own capacity by 13% (Figure 2).

According to the data of MAN Diesel & Turbo (MAN energy solutions, 2019), the power consumption in the Boil Off Gas supply unit in 8G90ME-C10.5-GI is 1.2 MW, and the mechanical capacity of the WHP unit is about 2.5 MW. The performance indicators for the WHR system are presented in Table 4. The available power is more than double the requirement of the gas fuel compressor, and this excess energy can be used for general ship needs.

Table 3. The parameters of the working fluid

Control point	Temperature, K	Pressure, MPa	Mass flow, kg/s	Working fluid	Control point	Temperature, K	Pressure, MPa	Mass flow, kg/s	Working fluid
1	308	0.78	214.3	SD	17	341	4.0	90	TL
2	341	0.81	214.3	SE	18	462	3.98	45	TL
3	341	3.72	214.3	SE	19	502	3.98	45	TL
4	333	3.17	214.3	SE	20	480	3.95	45	TL
5	333	3.77	214.3	SE	21	471	3.95	90	TL
6	364	3.75	214.3	SD	22	298	0.1	89.5	A
7	308	3.19	214.3	SD	23	471	0.42	89.5	A
8	364	3.77	1.15	H2	24	353	0.39	89.5	A
9	495	3.75	1.15	H2	25	310	0.38	89.5	A
10	339	0.81	1.15	H2	26	880	0.34	93.5	EG
11	308	0.79	1.15	H2	27	504	0.12	93.5	EG
12	298	0.1	130	W	28	354	0.1	93.5	EG
13	314	0.2	130	W	29	298	0.1	155	W
14	298	0.1	400	W	30	302	0.2	155	W
15	302	0.2	400	W	31	298	0.3	0.06	PL
16	341	3.9	90	TL	32	173	0,1	1.61	BOG

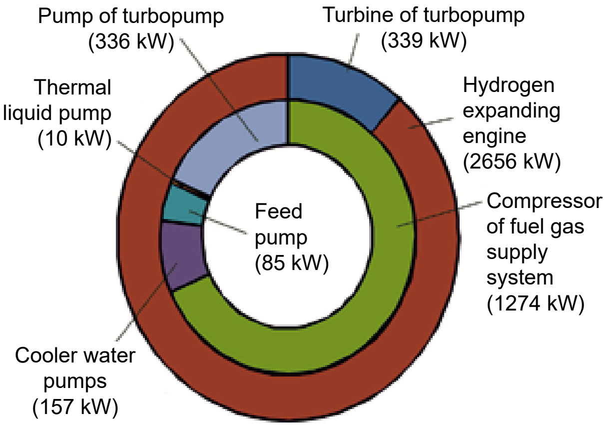


Figure 2. Components of mechanical energy of the disposal metal hydride unit

Table 4. Performance indicators

Performance indicators	Unit	Value
Diesel engine power	kW	42,600
Effective diesel engine efficiency	%	51.5
Gas fuel compressor capacity	kW	1.200
WHR system capacity	kW	2.500
Thermal efficiency of WHR system	%	21
Exhaust gas energy utilization factor	%	27
Total waste heat utilization factor	%	6.23
Relative capacity of the WHR system	%	6

The calculated total waste heat utilization factor for Rankine cycles are CRC – 4.03%; ORC – from 5.18 to 8.06%. As can be seen from the calculation results, the metal hydride technology has only a slightly inferior efficiency to ORC.

Conclusions

As much as 50% of fuel energy is lost via exhaust gases, coolant, etc. Modern two-stroke, low-speed diesel engines have low-temperature exhaust gases which do not exceed 520 K, which complicates the use of conventional waste heat recovery systems. Moreover, they are not efficient enough. Under such conditions, a WHR metal hydride system is a promising technology, and therefore the possibility of its application in a typical gas fuel supply system in LNG-powered ships was studied.

The simulation has revealed that the capacity of a WHR metal hydride plant ranges from 5.7 to 6.2% of a main engine. This exceeds the power required to drive the high-pressure gas fuel compressor, which reduces fuel consumption and carbon dioxide emissions. Therefore, the proposed system can be successfully used in LNG-powered ships as an auxiliary generator.

It is likely that the capacity of the power unit of the gas carrier vessel can be increased by burning the excess BOG in the afterburning device of the disposal metal hydride unit. Further research should be aimed at: conducting a techno-economic analysis of WHR metal hydride systems; studying the impact of engine load on the efficiency of the proposed system; and analyzing the influence of the proposed system on EEDI.

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