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WORLD MARITIME UNIVERSITY

Dalian, China

Study on Economy of Slow Steaming

By

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The People's Republic of China

A research paper submitted to the World Maritime University in partial Fulfillment
of the requirements for the award of the degree of

MASTER OF SCIENCE

In

MSEM

2020

DECLARATION

I certify that all the material in this research paper that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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Finally I would like to thank my tutor Professor Chen for the support to my dissertation, with his help I can finally finish my dissertation.

ABSTRACT

Title of Dissertation: **Study on Economy of Slow Steaming**

Slow Steaming is becoming a popular way of saving fuel oil in recent years, by slowing the speed of main engine to achieve the purpose of reducing fuel consumption and decrease the cost for fuel oil.

This paper focuses on the economy of Slow Steaming, trying to figure out the advantage and disadvantage of Slow Steaming. Slow Steaming can decrease the fuel consumption for a ship, however, it increases the time cost for one voyage. The time cost is delivered to the ship owner and the cargo owner, also the work load of seafarers is increased. The ship works in low load and at a lower speed with potential risk of mechanical issues and abnormal aging of equipments. Emission conditions become worse at this situation. All the long term and potential cost **must be balanced** by the saving of Slow Steaming.

In this case, if a ship is not designed to work at a low speed, the modern modifications can make the ship adjusted to the condition of Slow Steaming. Some suggestions are provided to relevant practitioners at the end of this research paper.

KEY WORDS: Slow Steaming, Economy, Ship Operating Cost, Emission, Modern Modification

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CHAPTER 1 : INTRODUCTION

1.1 Background Information

With the rapid development of the global industry and economy, the excessive exploitation and use of petroleum energy have aggravated the environmental pollution and the consumption of crude oil. In the face of various environmental problems caused by the world's massive carbon emission, such as global warming, ozone layer depletion, energy shortage, etc., it is urgent to solve the problems of pollution before treatment and the development of economy and industry at the cost of the environment. Many countries in the world have also put forward policies calling for energy conservation and emission reduction as an important requirement for shipping industry's development.

With the unprecedented development of international trade and shipping business, fuel cost has gradually become an important transportation cost for shipping companies. With the substantial growth of maritime freight volume, the continuous increase of ship tonnage, the high international oil price and other factors, reducing fuel consumption has become a new direction of shipping development.

With the development of the shipbuilding industry being almost saturated today, it seems difficult to solve the problem of energy conservation and emission reduction from the perspective of design and technology. In recent years, as a measure to deal with this situation, Slow Steaming has greatly reduced the fuel consumption of single voyage, which has been used by more and more ships. At the same time, it slows down the speed and reduces the fuel consumption, which seems to provide a new way of thinking for the shipping industry to temporarily solve the problem of energy conservation and emission reduction.

However, when the speed is reduced, the time cost of a single voyage increases instead, which reduces the transport ability of the ship under the condition of the same transport capacity. In other words, the transport efficiency of the ship is reduced instead. At the same time, when the running speed of Marine diesel engine is reduced, the emission of ships deteriorates, and the emission of harmful substances increases, which leads to the increase of the cost of ship renovation or the pollution of ship transportation. Moreover, the Marine diesel engine running at low power is also running at low efficiency, which greatly increases the aging rate of Marine diesel engine, increases the failure rate of Marine machinery, and increases the cost of repair and maintenance.

Under these considerations, this paper mainly analyzes the economy of ship operations by taking into account the fuel cost, time cost, maintenance of machinery and equipment, and the emission situation, as well as reducing the fuel consumption of a single voyage by Slow Steaming.

1.2 Review of Previous Research

Slow Steaming is brought up and studied by many parties and universities. As my domestic research, the papers focus on one point such as the side effect for diesel engine, the fuel consumption change and so on. Few papers focus on the emission or combine all these ideas to analysis the economy of Slow Steaming.

1.3 Objective of the Study

Throughout the research, this paper is trying to describe the economics of Slow Steaming concerning on fuel consumption, time cost, machinery aging and emission. Try to figure out if the total cost is decreased when fuel consumption seems drop on

Slow Steaming. And the modern modifications for ships to fit the condition of Slow Steaming.

CHAPTER 2 : Fuel Economy of Slow Steaming

2.1 The Relationship between Ship Speed and HFO Consumption

There is not only one diesel engine on the ship, only the diesel engine which drives the propeller in the propulsion system is regularly called the Main Engine. When the main engine rotates, the propeller is driven by gear box and stern shaft to provide forward or backward power for the ship. It is often necessary to consider the performance of the main engine and the performance parameters of the propeller in the design of the ship, and to match the parameters of the ship, so as to achieve the design speed of the ship.

For the ship main engine, whether it is directly connected with the propeller by shafting, or indirectly connected with the propeller by gearbox, clutch, or by other means, it always maintains the state of energy balance and runs at a certain speed. Once this balance is broken, the speed will keep changing until a new energy balance is achieved at a new speed. That is to say, when the ship is sailing steadily at a certain speed, the power emitted by the main engine is equal to the power absorbed by the propeller to propel the ship. For the convenience of discussion, various losses in the transmission are omitted. When the ship needs to change the speed, it is through adjusting the speed and power of the main engine to change the speed and thrust of the propeller, making it equal to the ship's resistance under the new speed. At this time, the power emitted by the main engine is still equal to the power absorbed by the propeller. When the ship's navigation conditions change, including navigation area, course, meteorology, hydrology, load capacity and ship pollution bottom, the ship's resistance changes, the power absorbed by the propeller will also change accordingly, which directly affects the main engine, so that the power and speed of the main engine will also change with the change.

As described above, no matter how the main engine is connected to the propeller, whether it is directly linked through the stern shaft or through the gearbox, the main

engine works according to the propelling characteristics of the propeller. According to the power requirements of the main engine propeller, the power of the main engine speed to the third power is proportional to the power of the propeller, in other words, the propulsion performance of the ship is proportional to the third power of the main engine speed.

P_e = the power of the engine

P_p = the power of the propeller

C_n = the speed of the engine

$$P_e = P_p = C_n^3$$

Also we can calculate the following table.

Table1 - Relationship between engine power and engine speed

The power of engine %	25	50	75	90	100	110
The speed of engine %	63	79.5	91	96.5	100	103

When a ship operating in a stable condition, the thrust of propeller T_e ($T_e = C_1 \cdot N_p^2$) is equal to the resistance of the ship R ($R = A_r \cdot V_s^3$)

$$A_r \cdot V_s^2 = C_1 \cdot N_p^2$$

A_r - the ratio of the resistance C_1 - the ratio of the thrust V_s - ship speed

N_p - propeller speed

In the formula, the ratio of the resistance and thrust is fixed to the ship.

From the study of the main engine, the fuel consumption is proportional to the engine power, while the engine speed is proportional to the propeller speed as well as the ship speed.

From the analysis we can see, the cost of increasing same speed at low and high ship speed is totally different. The fuel consumption and power price is higher in low efficiency. And, we ignore the resistance increasing at higher ship speed, so we can see the difference.

2.2 Fuel Consumption in Slow Steaming

To calculate the fuel consumption (b_m , kg/n mile) related to the engine speed.

$$b_m = B/V_s$$

B - the fuel consumption per hour(kg/h) V_s - ship speed(n mile/ hour)

When the ship load is fixed and the transmission loss is ignored, the power of propeller is equal to the engine power, with a fixed ratio the formula is following:

$$N_e = P_p = A V_s^3$$

N_e - the effective power of engine P_p - the power of propeller

A - the fixed ratio

$$b_m = B/V_s = (B/V_s)(A V_s^3 \eta_e) = A B_e V_s^2$$

B_e is the fuel consumption rate (kg/HP h)

Thus, for the same ship with the same load, the engine power is proportional to the power of the engine speed as well as the ship speed. The fuel consumption is inversely proportional to the power of the engine speed.

So a slight decrease in the engine speed can obviously reduce fuel consumption.

2.3 The Time Cost at Different Ship Speeds

From the formulas above, we already know the engine speed is proportional to the propeller speed and ship speed, so if we decrease the engine speed from 15%, the ship speed decrease to 85% as normal as well.

So we can use a table to see the relationship between the ship speed and the time cost. To be clarified, only the fuel consumption and time cost be considered in this part in different engine speed, in order to show the engine speed and total fuel consumption.

Table 2 - Fuel consumption in Slow Steaming

	Speed 100%	Speed 90%	Speed 85%	Speed 75%
Ship speed	100%	90%	85%	75%
Fuel consumption	100%	72.9%	61.41%	42.19%
Voyage time	100%	111.11%	117.65%	133.33%

	Speed 100%	Speed 90%	Speed 85%	Speed 75%
Total fuel consumed	1	81%	72.25%	56.25%

The rough calculation shows if the engine speed decreases, though the time cost is increased, the total fuel consumption is still reduced. Theoretically, the lower the engine speed is, the more fuel is saved, the longer the voyage takes. We can simply conclude the Slow Steaming can reduce the fuel cost for the ship operator and company in theory.

2.4 Economic Cost

2.4.1 The effect on cargo owner

There are two main effects on cargo owners when the ship operates in Slow Steaming: one is the effect on cargo owners' inventory cost, the other is the effect on cargo owners' market cost. These two are called in-transit inventory costs.

- (1) Impact on inventory costs: inventory cost refers to the direct and indirect expenses incurred during the period from goods being purchased to goods being put into the market to earn profits. When the ship slows down, the sailing time of the ship increases, the delivery time that the cargo owners can expect will be correspondingly delayed, the time of goods at sea becomes longer, the possibility of damage of goods increases, inventory cost and opportunity cost increase correspondingly, especially the impact on high-value goods is greater. The extension of profit cycle also increases the cost of shippers.
- (2) Impact on market costs: If there are time-dependent goods in ship transporting, Slow Steaming will affect the storage period of the goods or delay the listing of the goods. For example, for chilled and quick-frozen products, the increase of

transportation time may lead to the shortening of the remaining shelf life and affect the sales cycle. And this kind of goods every day delay to market may lead to different degrees of reduction in the selling price, a disguised increase in the market cost of shippers.

2.4.2 The effect to ship owner

The operating cost of a shipping company is very complicated. In this paper, the operation cost is simply divided into labor cost and material cost.

(1) Increase of manpower costs: in Slow Steaming, due to the increase of sailing time and the increase of voyage times, the manpower cost increases due to the long voyage of seafarers at sea. As the engine speed slows down, the mechanical equipment operates in a worse condition and the maintenance cost of manpower increases, which will be analyzed in detail later.

At the same time, the proportion of the ship's sailing time at sea and the time mooring at the port changes, so does the fatigue situation of the crew, the working intensity of the crew increases as well. Hidden risks such as changes in weather and sea conditions and increased chances of improper operations caused by personnel fatigue also increase the cost of shipping correspondingly.

(2) Changes in material costs: the Slow Steaming effectively reduces the fuel consumption of the ship and the fuel cost of the ship operating company. Similarly, when the speed is reduced, the maintenance cost of the ship increases, the time cost of transporting goods increases, the aging speed of the ship is accelerated, and the profit cycle is longer. All these increase the operating cost of the ship and other expenses of the shipping company. It is hard to tell whether the ship's Slow Steaming has actually reduced the shipping company's true costs.

Also, the calculation about the fuel consumption can only get the figure of the amount of the heavy fuel oil. The real capital cost for HFO is related to the International real-time crude oil price, so the savings of Slow Steaming floats as

well. Affected by the COVID-19 and the conflict between the US and OPEC, the crude oil price has dropped to a historical low point. The international crude oil futures price may even drop to a negative price in future. The amount of crude oil produced and price oscillation. So the fluctuations of the crude oil price will substantially influence the capital savings of the shipping companies in Slow Steaming.

2.5 Fluctuations of the International Crude Oil Price

The price of crude oil is not stable, it changes all the time influenced by many factors such as the storage of oil and the production mass of crude oil. Meanwhile the US dollar currency rate and the growth of international economic will also change the price. Since the crude oil will also matter the national strategy, the relationship between nations will influence the policy on oil trade, the price would be different when situation become different. The crude oil is not only the cargo for ship transporting, also a main factor of the cost of ship transporting, so the price matters a lot for marine market.

Figure 1 - Crude oil price in past 20 years, WTI,CFD,CL



Resource: Sina Finance,

<https://finance.sina.com.cn/futures/quotes/CL.shtml>

According to the figure we can see the international price of crude oil (the example is WTI oil CFD) is changing all the time. WTI is West Texas Intermediate, one kind of light crude. The NYMEX WTI crude contract serves as the benchmark for internal and international crude price. The price changes from around 20 USD/barrel to 147.27USD/barrel. Even in 2020, the crude future trade price drop into a negative price affected by the changes of international relationship and COVID-19. The price of crude oil can directly change the price of bunker oil and the orders for crude and crude products. Low oil price would stimulate the VLCC and LNG shipping. And also will make engineering ship industry go recession.

According to Part 2.3 in this paper, the bunker oil cost for a voyage will change with the decrease of ship main engine speed. When the ship speed decrease 15% of the normal speed, the fuel mass cost would decrease to 72.25% of normal fuel oil consumption as showed in Table-2. Combined with the current crude oil price, as well as the maritime bunker oil price, and the fuel saved by Slow Steaming, the capital saving for a single voyage on a particular ship can be calculated.

CHAPTER 3: Emissions and Abnormal Mechanical Aging due to Slow

Steaming

When the ship operating in Slow Steaming, especially when the power of the main engine is reduced to less than 50% of the rated power, it will cause improper combustion in the cylinder of the diesel engine, increase the lubricating oil consumption rate, and cause serious gas pollution to the combustion chamber components, exhaust system and pressurization system. Causes the exhaust back pressure to rise, the scavenging pressure to drop, the exhaust temperature to rise.

People's requirements for environmental protection are becoming increasingly stricter, and ship gas emission sources are also getting more and more attention, mainly including SO_x, NO_x and particulate emission PM.

Limiting the sulphur content of heavy oil proposed by IMO can effectively avoid the SO_x in ship exhaust gas content, but because of the the working environment is poor in combustion chamber of diesel engine onboard, it is hard to avoid the generation of NO_x and particle emission at the same time also can change as conditions and difficult to avoid. So this article will focus on NO_x and PM quantity and speed of diesel engine at work.

3.1 Emission conditions when engine working at a Low Speed

3.1.1 NO_x Emmission

In large two-stroke low-speed diesel engines, NO_x production mainly has the following factors, the maximum explosion pressure, scavenging air temperature and scavenging air back pressure, because the environmental conditions are not considered in this paper, so it is not discussed.

In this part, the NO_x emission will be discussed according to a diesel engine testbench report to analysis the working conditions and the NO_x emission.

3.1.1.1 NO_x Emission with Max Burst Pressure

The maximum burst pressure of diesel engine has a great influence on the production of NO_x. Injection timing is generally determined by the camshaft of the main oil pump, which is affected by the adjustment of VIT equipment and oil pump gasket.

According to the testbench test report of 6S60MC main diesel engine, as following table.

Table 3 - Relationship between NO_x and max burst pressure

resource : testbench report of the 6S60MC engine.

Load	Comment	B.Press	Pcomp	Pmax	Pscav	Tscav	Air	NO _x
100%	Pmax-6	300	128.4	135	3.62	37	5.51	14.98
100%	Pmax-3	300	127.0	138	3.58	37	5.46	15.51
100%	Ref.	300	125.9	141	3.55	37	5.41	16.00
100%	Pmax+3	300	124.7	144	3.52	37	5.37	16.51
100%	Pmax+6	300	123.6	147	3.49	37	5.32	17.01
75%	Pmax-6	225	97.3	123	2.75	32	5.66	15.01
75%	Pmax-3	225	96.2	126	2.72	32	5.60	15.50
75%	Ref.	225	95.1	129	2.69	32	5.54	16.00
75%	Pmax+3	225	94.3	132	2.67	32	5.49	16.46
75%	Pmax+6	225	93.3	135	2.64	32	5.44	16.98

In the table,

B.press - exhaust back pressure mmWC

Pcomp - compression pressure bar

Pmax - max burst pressure bar

Pscav - scavenging pressure bar

Tscav - scavenging temperature °C

Air - the mass of scavenging air kg/BHP.h

NOx - the mass of NOx in emission g/KW.h

The table shows the emission condition in different engine working burst pressure, when engine working in 100%load and 75%.

In figure we can conclude the NOx emission rises with the burst pressure arises.

3.1.1.2 NOx with Scavenge Temperature

The scavenge temperature or the inlet temperature of main engine is influenced by the adjusting of inter cooling system. In table 4 will show the NOx emission change with the intake temperature changes.

Table 4 - Relationship between NOx and scavenge temperature

Load	Comment	B.Press	Pcomp	Pmax	Pscav	Tscav	Air	NO _x
100%	Tscav-6	300	124.5	141	3.50	31	5.35	15.87
100%	Tscav-3	300	125.4	141	3.53	34	5.39	15.92
100%	Ref.	300	125.9	141	3.55	37	5.41	16.00
100%	Tscav+3	300	126.3	141	3.57	40	5.44	16.09
100%	Tscav+6	300	127.2	141	3.60	43	5.48	16.14
75%	Tscav-6	225	94.0	129	2.65	26	5.47	15.88
75%	Tscav-3	225	94.5	129	2.67	29	5.51	15.94
75%	Ref.	225	95.1	129	2.69	32	5.54	16.00
75%	Tscav+3	225	95.6	129	2.71	35	6.58	16.07
75%	Tscav+6	225	96.1	129	2.73	38	5.62	16.13

temperature in combustion chamber when engine working in working stroke. When working in the same load, adjusting the inter cooling system to decrease the scavenge temperature can reduce the emission of NO_x.

3.1.1.3 NO_x with Exhaust Back Pressure

Scavenge pressure depends on the size of turbo charger, environment and exhaust back pressure, the exhaust back pressure can be measured and adjusted. Suitable back pressure can keep engine working in good condition, in Table 5, the NO_x emission and exhaust back pressure will be showed.

Table 5 - Relationship between NO_x and exhaust back pressure

Load	Comment	B.Press	Pcomp	Pmax	Pscav	Tscav	Air	NO _x
100%	Pback-200	100	127.3	141	3.59	37	5.50	15.93
100%	Pback-100	200	126.6	141	3.57	37	5.46	15.97
100%	Ref.	300	125.9	141	3.55	37	5.41	16.00
100%	Pback+100	400	125.1	141	3.53	37	5.37	16.04
100%	Pback+200	500	124.3	141	3.51	37	5.33	16.09
75%	Pback-200	25	97.2	129	2.75	32	5.70	15.88
75%	Pback-100	125	96.2	129	2.72	32	5.62	15.94
75%	Ref.	225	95.1	129	2.69	32	5.54	16.00
75%	Pback+100	325	94.3	129	2.67	32	6.47	16.03
75%	Pback+200	425	93.2	129	2.64	32	5.39	16.09

We can see the NO_x emission rises with the back pressure arises, with means the engine spend more work to exhaust, the worse combustion condition is, and the NO_x emission rises.

3.1.1.4 Slow Steaming and NO_x Emission

NO_x is normally NO and NO₂, the main part is NO. NO is generated in 3 ways, the first is generated by heat, second is temporary and the last is generated because of the N in fuel.

The NO is mainly generated in the combustion phase, the N₂ in air and O₂ react with the heat of combustion. In exhaust the NO partly react and become NO₂, and in exhaust gas, the content of NO_x is NO and NO₂.

As for a ship in a voyage, the Slow Steaming is to reduce the speed and load of main engine. The change of working conditions and settings is showed to the air-fuel ratio, the change of air-fuel ratio lead to exhaust back pressure to rise, scavenge pressure drop, exhaust temperature rises and finally leading to NO_x emission arise.

3.1.2 CO, HC and PM Emission

As discussed before, the reduced speed and load can lead to worse combustion conditions in cylinder, the changed air-fuel ratio make the combustion incomplete, and lower scavenge pressure make air and fuel less mixed.

In an idle and low load working condition, the temperature in cylinder is low, the fuel drop is not totally atomized, the fuel spray goes out of flame area and is hard to be ignited. And the post-ignition could not totally consume the fuel spry in combustion stroke. The fuel is directly exhausted to the air, the HC content in exhaust gas rises.

When combustion is incomplete, the CO content and PM content rise as well.

If the exhaust gas dealing devices are not installed onboard, the emission condition in Slow Steaming will be worse and the fuel efficiency will be decreased.

If a ship is going to voyage in low engine speed, the ship need to be designed to voyage in low engine speed, otherwise the ship need to be modified. The exhaust dealing devices, fuel units and other equipments and devices need to be installed onboard to fulfill the requirements of exhaust gas.

3.2 Mechanical Issues and Abnormal Aging

Slow Steaming is an effective way to save fuel, but if the ship operates in Slow Steaming for a long time will cause the combustion condition in cylinder is poor, lubrication oil consumption rate increases, so that combustion chamber components, exhaust system and turbo system will suffer serious gas pollution. Due to the exhaust pipe, exhaust gas boiler, chimney, turbo charger, intake and exhaust valves, air cooler, the turbo charger exhaust back pressure increased, the speed decreased, resulting in the decrease of diesel engine scavenging pressure, increase of exhaust temperature, decrease of operating performance, even the normal load work can not be restored.

The potential risk in the main engine is the damage to crankshaft and bearings, abrasion of cylinder liner and piston and the damage to turbo and exhaust boiler. The bearing support load is proportional to the speed of crankshaft, when engine operating in low speed, the bearing load become larger as well as the dynamic oil film thinner and even hard to form. Lack of lubrication will lead to abnormal abrasion of shaft bearing.

The piston works in cylinder repeatedly, the lubrication depends on the oil film of cylinder oil. The flimsy oil film is easy to crack as well in low speed of engine. The worst part is the upper of cylinder at the TDC and the lower part near the scavenging ports while the middle part is less damaged. In addition of the horizontal force of piston when low speed running.

Decreasing the speed of engine means the intake and outlet air mass will drop, the turbo speed will drop as well, the mixed air in cylinder can not be changed and the combustion will be in low air-fuel ratio, the combustion condition will become worse. The carbon deposit and incomplete ignited fuel will accelerate the damage and aging of the engine. Mixed air gets into the scavenge box may cause fire accident, the turbo speed drop and working under risk of gathering deposit sediment, which will cause the damage of turbo working parts. Low exhaust pressure and temperature will also increase the risk of low temperature corrosion and durchfressen.

All those above will lead to mechanical problems and abnormal aging of the main engine.

Also, when engine working in low speed, the lubrication condition will be worse. Low working speed will weaken the dynamic lubrication oil film, which will lead to the working moving parts abnormally abrasion and corrosion. Long-term low speed working also will influence the cylinder oil consumption rate, make cylinder working condition and lubrication condition worse and aging. The fuel unit working in low load and speed could also cause misfire and post-combustion, the potential risk of knocking and damage will increase.

As for the auxiliary machinery, the main engine working at a low speed of main engine working will lead to the aging and malfunction of the exhaust and intake equipment, which will cause extra working load of seafarers and cost for shipping companies.

Slow Steaming will also increase the working load of steering equipment, since the ship speed decreases, the efficiency of steering gear drops, the steering gear needs to move at a larger angle and the speed to maintain the normal steering gear efficiency.

So that, for a ship's voyage in a long-term Slow Steaming condition without any modification to the ship could decrease the fuel consumption and save the fuel cost, but take the long view, the cost of mechanical risk and aging as well as the increase of the emission is critical.

3.3 New Requirement for Non-sulphur Bunker Oil and Risks in Voyages

The IMO Maritime Environmental Protection Committee sulphur Limit order, which came into effect on January 1, 2020, stipulated that the sulphur content of the fuel oil of ships worldwide should not exceed 0.50%*m/m*, and various countries put forward more stringent restrictions in the restricted area.

In order to meet the emission requirements of sulphur, the ship owner could choose to use low sulphur content bunker oil or use exhaust gas dealing devices to achieve the goal. The water spry device or SCR system could be used.

As for low sulphur content bunker oil, most ships are designed to operate with normal bunker oil. A change of bunker oil could cause mechanical risks of malfunction in devices onboard.

The low sulphur content bunker oil risks including the quality of oil, the fit with the cylinder oil and lubrication oil as well as the machinery onboard and the compatibility with engines and other low sulphur bunker oil. All above could be risks to endanger the safety of ships and human life.

Meanwhile, the low sulphur content bunker oil has different physical properties, which means the bunkering, storing and main engine and generator diesel engine

may suffer worse working condition in fuel system and combustion chamber. Lower viscosity and more additives may add the risk of blocking the pipes, filters, pumps and injectors, which may cause main engine abnormal working condition or whole ship blackout even worse conditions. The additional workload, unexpected damage or worse situations which may endanger the safety of the ship may happen.

Low sulphur content bunker oil have more additive, the Al and Si content increase which could lead to abnormal abrasion or corrosion in moving parts. Lower viscosity decrease the lubrication ability of fuel oil, increase the cost of heating the bunker oil. The stronger volatility of low sulphur oil make the bunkering and storing harder and the crew need to pay more attention to.

CHAPTER 4: Modern Modification of Ships

Slow Steaming is a popular and effective method to reduce the fuel consumption for a ship, however the side effect of Slow Steaming such as the emission and mechanical issues will increase the cost of time, capital, seafarer work force and potential risk. The ship can sail in Slow Steaming has to be in circumstances of the ship is designed to be good at Slow Steaming. If a ship reduces the main engine speed without any modification of ship main propelling system, the problem would be worse in long-term view.

Meanwhile, the Slow Steaming does save the cost of fuel, the fuel cost also depend on the international crude oil price. The crude oil price can be influenced by many factors. This year of 2020, because of the conflict between OPEC and US, the crude oil price drop to an incredible level. Also, the price can be influenced by politics and relationship between nations. With the drop of the oil price and the impact on the normal industry because of the COVID-19 outbreak, the balance of saving fuel cost and saving cost for operating a ship seems need to be reconsidered.

On the one hand, the fit of propeller, main engine and ship is fixed when ship is designed. Also, the efficient working condition is also fixed. If we keep a long-term Slow Steaming operating onboard without any change of the mechanical equipment, the ship would working in “uncomfortable” condition for long time, the risk of fault would rise obviously.

On the other hand, with the convention of sulfur content in fuel oil, the modern modification of ships is necessary. Since then, the ship can be modified to fit the long-term Slow Steaming operating and lower the cost for mechanical costs as well as slowing the pace of ship aging.

4.1 Exhaust Gas Treatment (EGR, SCR water spray)

To deal with the emission issue, the exhaust gas treatment devices are necessary, as the convention of sulfur in fuel oil, the SO_x content in exhaust gas can be controlled. The PM content and the NO_x in exhaust gas need to be neutralized.

To deal with the PM content, we can focus on two phases. The first is to prevent of generating, the second is to not outlet into the environment. In this case we can decrease the amount of PM generated and keep the PM not into the environment.

In order to prevent the PM from generating, we can optimize the scavenging air in oxygen content, pressure, temperature, humidity and amount to improve the mixing of fuel and air, change the combustion condition, make the fuel totally ignited and consumed. Even the main engine working in Slow Steaming, the PM content can be controlled.

Otherwise, the EGR system (Exhaust Gas Re-circulation system) can be used onboard. The system can lead part of the exhaust back to combustion chamber to involve the ignition stroke. The CO₂ and water in exhaust gas can increase the heat capacity in combustion chamber, which could slow the combustion phase and lower the combustion temperature, make the mixture of fuel and air totally consumed. In this condition, the NO_x and PM will be hard to form and make the main engine work better in low speed and heavy load.

Outside the engine, the methods of dealing with the PM are easy, the BMW B series gasoline engine have a new part GPF(Gasoline Particle Filter). The GPF is more like a filter to file the particles out of the exhaust gas, the same way could be used onboard. Also the centrifuging devices, water spay device, exhaust catalyst, exhaust reactors and even the electrostatic capture device can be installed onboard to deal with the PM content in exhaust gas.

SCR (Selective Catalytic Reduction) is a brand new technology to deal with the NO_x content in exhaust, the SCR system can make NO_x react with NH₃ with

catalyzer and make NO_x back to N₂. The SCR device can lower the NO_x content by 50% with low price urea without change the structure of main engine and with a low heat rejection.

With the EGR, SCR and water spray devices installed onboard, along with other exhaust gas dealing devices, the emission issue on Slow Steaming could be controlled. The fuel efficiency and NO_x&PM emission problem could be solved.

4.2 Optimization of Fuel Unit

When engine working in Slow Steaming condition, the main engine may suffer the worse working condition and lead to mechanical issues. For long-term Slow Steaming working, the fuel unit need to be upgraded.

When the engine is working at a low speed, the atomization of fuel oil may cause the incomplete combustion and cause the particles and post-ignition, and the fuel injection may be damaged. The engine setting and fuel unit need to be optimized. The compression ratio can be increased and the injection angle can be advanced. The fuel pressure should be increased and increase the temperature of cooling water as well as the scavenging air.

In daily maintenance, the engine load management should be improved. In long-term Slow Steaming working, the accelerate of engine should be slow, and avoid the critical speed and load. Engine working parts and sealing condition in combustion chamber should be checked after finishing engine. The scavenging box should be checked and cleaned more frequently. Random blowing of engine is also necessary, during long-term Slow Steaming working, short blowing of engine could improve the working condition of engine and auxiliary machinery in exhaust side.

The turbo charger needs to be cleaned with schedule, the turbo blades should be cleaned by water both on compression side and exhaust side. Turbo charger cleaning

should follow the instruction of the supplier and perform with caution. Frequent cleaning of turbo can remove the carbon deposit and keep the dynamic balance of turbo blades. The exhaust pipe can be unblocked to keep the exhaust back pressure.

In this case the fuel atomization condition can be improved, the combustion could consume the fuel and decrease the particle content in exhaust gas, the fuel efficiency could be improved, the auxiliary machinery working condition could be improved to avoid the potential risk.

4.3 Engine Working Data Analysis

Data analysis is necessary to monitoring the condition of main engine. According to the engine management system the data of engine can be easily acquired, with long-term monitoring and analysis, the performance attenuation can be noticed. With the decay of engine output, we can process the data to perform an accurate trouble-shooting and avoid the potential risk to the engine damage or delay of voyage plan.

With data gathering and processing, the engine working condition can be compared in every data or figure. The abnormal temperature, pressure, torque, flow rate, consumption rate, speed or even a noise can lead to engine aging or malfunction, the risk of damage or accident should be avoided in every circumstances.

So the normalization of the main engine parameters and figures analysis can make it easier locating potential risks and trouble shooting. The abnormal figures in a voyage condition should be noticed in the template, and with the long-term data analysis we can be aware of the aging of the parts and make accordingly plans to perform a maintenance or a repair for the part.

CHAPTER 5: CONCLUSIONS and LIMITATIONS

Slow Steaming is a popular way and an effective way to control the fuel consumption, and be used widely in shipping industry. Through the study I find simply decrease the speed of main engine may save the fuel cost for ships, but in other ways such as the time, mechanical, market and the emission, the cost may increase if the ship just slow down the speed of the main engine.

With the study, we can get to know that the emission will increase with the decrease of the engine speed. The NO_x and PM as well as the CH content will increase without any exhaust dealing devices. The conventions about the pollution and the emission is becoming more critical and in 2020 the sulfur content will be more strict. The increased emission is not acceptable.

When Slow Steaming makes the engine work in “uncomfortable” conditions, it will make the engine work with low efficiency, accelerate the aging process and lead to potential risks. Slowing down the engine speed will make the combustion conditions worse and more vibration will result. Also the turbo and exhaust system will suffer worse working conditions. Accelerated aging speed will cause the engine’s performance to decay and risks of accidents will be inevitable, as a result the cost of repairing and maintenance will rise accordingly.

To fit the requirements of saving fuel and environment protection, the upgrading of ship equipment, or in other words, modern modification is necessary for the ships.

Modern modification can make ship to adjusted to the long-term Slow Steaming working conditions and meanwhile the emission condition can be controlled. With the upgraded engine and exhaust dealing devices, the engine could handle the low speed working condition even when the ship is not designed to make its voyages at such a slow speed. The working load of auxiliary machinery can be reduced and the maintenance cost can be saved as well.

Slow Steaming without the modification is not saving capital for shipping companies in the long run if balanced with the additional costs. Modern modification can make the cost into a one-time investment. Even the slow ship can increase the cost of market and time, balance with all cost is still a good deal. And with the methods mentioned in the paper, the unwanted aging and risks can be avoided.

This paper does have its limitations in some way, the points above need to be further studied. This is due to lack of relevant information, data and deeper knowledge background, so these are only the tentative views of the author on Slow Steaming with his limited research efforts and any comments by the readers will be welcome.

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