The Effect of Voyage Path on Condition Based Monitoring of Cylinder Liners

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Cylinder liners and piston rings conditions are vital for continuous running of an engine. There are few studies about how the environment can affect cylinder liners and piston rings of metallic wear in 2-stroke slow speed engine. The paper aim is to include environmental effect on model of condition based monitoring (CBM). By considering environment impact on metal wears rate that is generated from cylinder liner. We monitored iron particle and residual Base Number (BN) of drain cylinder oil from 2-stroke slow speed engine that sail in different atmosphere. All ships monitored start sailing from Japan ports to US ports and another set of ships from Japan ports to Australia and New Zealand ports. Condition based monitoring on cylinder liners current in-use do not put the prospect of sailing environment as factors that can affect diesel engines. From analyzed drain oil results showed that ships sailing to Australia and New Zealand ports generate more of metallic element than ships sailing to US.

Key Words
Condition based monitoring, Base number, Wear, Cold corrosion, Cylinder lubricant oil

1. Introduction

Most ocean sailing ships are being power by diesel engine running on heavy fuel oil or other fuels. Heavy fuel oil is preferred as fuel for 2-stroke slow speed engine, because of high calories, affordability and availability at both minor and major seaports. Fuel oil is residual fuel from crude oil refinement and for 2-stroke slow speed engine to utilize fuel oil several equipment function in parallel to improve fuel oil chemical properties for combustion. The complexity in design of 2-stroke slow speed diesel engine contributes to the risk of mechanical failure when burning fuel oil.

In 2-stroke slow speed engine lubricating oil require are system oil and cylinder oil. System oil lubricate crankshaft of the engine while cylinder oil lubricate cylinder liners and piston rings. Cylinder lubricating oil (CLO) is produce to compensate severity of operation crosshead slow speed engine mounted on merchant ships. All mineral oil has Base Number (BN) property to compensate fluidity of circulating oil in the systems. CLO requirement for 2-stroke engine is very strict and must attain the challenges of keeping cylinder liner and piston rings lubricated despite under severe operating conditions. To attain these requirements CLO is doped with additives for acidic neutralization, carbon cleaning and keeping cylinder liners wet after each stroke.

Lubricant makers introduce model for optimization of feed rate while monitoring cylinder liner wear of Fe particle by testing of drain cylinder oil. The model levels have different, which are Caution, Alert and Optimal or safe. By analyzing residual TBN and Iron wear metal in drain cylinder oil using onboard test kit. There are other tools for maintenance and management of cylinder liners and piston rings such as time-based maintenance, dynamic maintenance planning and condition based maintenance (CBM). Among afore mentioned approach this paper will centered on CBM method, analyzing of drain CLO which is effective approach for monitoring cylinder liners of two-stroke diesel engine. CBM is a strategically maintenance management through data collection and monitor of trend of physical asset in operation. The research on on-line wears condition-monitoring system for marine diesel engine focus on detecting particles and lubricant quality detection base on shaft torque moment and instantaneous rotation velocity detection. With selectable trend of analyzed CLO results, it will elevate decision on maintenance schedule on equipment. CLO trend analysis is utilize either before data deviation occurs or during machinery down time decision.
for equipment. CBM for 2-stroke slow speed marine engine depend on CLO scrape down oil from piston rings and cylinder liners.

CLO contains certain amount of alkali 4) to neutralize sulfur acids formed during combustion of marine fuel oil and the maximum acceptable percentage of sulfur in fuel oil is mostly use for selection CLO BN grade. CLO is not produce in view of sailing environment for ship, rather suitable for engine operation and thermodynamics mechanism of piston rings with cylinder liners. More also, it contains additives to aid additional CLO qualities such as liner polishing, wear and impurities particle absorbing and thermal stress reliability 6).

2. Equipment and Materials

2.1 Vessels Details

Four ships that make use of only 2-stroke slow speed engines and it is mounted on pure car carrier (PCC) ships have fixed call ports. At the period of monitoring these engines running on heavy grade fuel oil of 380cST and max of 3.5% of sulfur contents. The air charge into combustion section is compressed to certain temperature, mix with atomize refine heavy grade fuel oil and CLO resulting to ignition. During combustion phase CLO qualities is crucial for continuous operation, when using fuel oil with high viscosity, high density, and long combustion period, CLO must able to expand rapidly and withstand long duration of thermal energy generated during combustion. The ash and carbon soot produce will be absorbed by CLO film. And incomplete combustion and unburned fuel oil can lead to severe instabilities of CLO qualities during lubrication of cylinder liners and piston rings. Table 1 is the engine model details for ships according to their route.

2.2 Wear and Lubrication

In 2-stroke slow speed diesel engine atomize fuel oil and compress air are discharge into the cylinder during piston inward stroke for the ignition to occur 5), when ignition phase is completed next is combustion phase that increase thermal energy and internal pressure. In modern 2-stroke slow speed engine, the piston distance has become longer requiring CLO to be more fluid despite under thermal stress without losing any of its properties. Long stroke in slow speed engine is characterized by their ratio of piston to cylinder diameter and this depends on manufacturer design. Since the subject engine designed is long stroke, it has increase probability of mechanical failure because of deficiency in lubrication by CLO resulting to metal-to-metal wear.

For CLO to be relevant at least it is require to be fluid enough to wet metallic surface of cylinder liners and piston rings, and when 1g of oil is feed into cylinder liner it should be able to lubricate surface area of about 10m² above and piston stroke of 4.5 m above. In severe environment there are various factors affecting engine internal combustion, these can be unstable fuel oil viscosity, variation of sulfur contents, cylinder oil quality and onboard handling of CLO. These factors can affect cylinder liner wear quantity per stroke and piston rings depreciation.

CLO circulating in the engine is not re-circulated but drain to waste oil tank. This makes it more reliable to monitored cylinder liners and piston rings through tribology of drain CLO. Cylinder liners wear can be abrasive, adhesive or corrosive wears in nature. Abrasive wear is caused by hard particles contamination from marine fuel oil such as catalyst fine (Al+Si). When insufficient lubrication of cylinder oil leading to metal-to-metal contact, it is adhesive wear and on the other hand corrosive wear (Cold Corrosion) is combination of abrasive and adhesive in corrosive environment of unstable sulfur oxide films which are the products of equation (1) and equation (2). Cold corrosion occurs when engine temperature drop resulting to build up between heat exchanger and engine cylinder which is condense to sulfuric acid on the liner walls and mostly found at the top section of cylinder liner 7). As for the combustion of fuel oil, the sulfur reaction stages is summarize in the below chemical reaction equation and corrosive acid substance is formed with the aid of sulfur from fuel oil, air and water, which is represented as below,

\[
\begin{align*}
S_8 + O_{2(g)} &\rightarrow SO_{8(g)} \\
2SO_{8(g)} + O_{2(g)} &\rightarrow 2SO_{8(g)} \\
SO_{2(g)} + H_2O &\rightarrow H_2SO_3(aq) \\
SO_{8(g)} + H_2O &\rightarrow H_2SO_4(aq)
\end{align*}
\]

In equation (3) sulfuric acid anhydride in aqueous state react with water vapors, and water molecules are always present in the marine fuel oil as shown in Table 7, only 0.5% max volume of water is acceptable for marine fuel. Compressed atmospheric air has trace amount of H₂O to produces sulfuric acid in aqueous as shown in the equation (4). When 2-stroke engine is operated at extreme slow speed, the amount of sulfuric acid condensed on the

| Table 1 Vessels engine specifications |
|--------------------------------------|
| American Vessels (AV) | Oceania Vessels (OV) |
| Model | 6UEC60LSA | 7UEC60LSII |
| Max Power (kW) | 11,180 | 14,315 |
| Number of Cylinders | 6 | 7 |
| RPM | 110 | 105 |
| Bore size (mm) | 600 | 600 |
cylinder liners, due to increase in low temperature and favorable dew point for H₂SO₄ vapors. Thus cold corrosion environment is set-up on cylinder liners surface and CLO property can become deficient then causing cold corrosion that affect cylinder liners with piston rings when gliding.

Cold corrosion deprives necessary characteristics of CLO to support movement of piston at top dead center to bottom dead center. The effects of sulfuric acid formed on the cylinder walls are defined by concentration and cylinder liner temperature. It has been studied that acid with strength ranging from 3 up to 20% is the most active in reaction with cast iron.

The internal combustion of sulfur in equation (2), the chemical reaction product is unstable sulfide oxide molecule that reacted with water molecule producing acidic oxide. As vessels sail to different route, the percentage amount H₂O in compressed air from surrounding seawater may vary depending on route of the sailing. In this project we monitored 2 different sailing routes, which are ships sailing to US ports and another ships sailing to Oceania countries ports.

Tables 2 and 3 represent engine conditions at sampling of drain CLO sampling from Oceania Vessels (OV), while Tables 4 and 5 represent American Vessels (AV).

### Table 2  Engine conditions @ sampling for Ocean Vessel 5 (OV5)

| Total Eng. Hrs. | Temp C | Scav. Air Press. (bar) | Power @ sampling (kW) | Main Eng. RPM @ sampling | Consumption Ltr/day | BN (Used Oil) | Fuel Sulfur % | Cal. Feed Rate g/kWh |
|----------------|--------|------------------------|-----------------------|--------------------------|---------------------|--------------|--------------|-------------------|
| 71695          | 42     | 0.15                   | 12203                 | 102                      | 408                 | 36           | 2.49         | 1.30              |
| 72328          | 41     | 0.16                   | 12098                 | 102                      | 408                 | 52           | 2.49         | 1.32              |
| 73092          | 42     | 0.15                   | 12012                 | 101                      | 408                 | 47           | 2.49         | 1.30              |
| 72971          | 41     | 0.15                   | 12211                 | 101                      | 408                 | 52           | 2.49         | 1.32              |
| 81297          | 37     | 0.16                   | 12417                 | 102                      | 420                 | 43           | 2.64         | 1.32              |
| 81478          | 33     | 0.16                   | 12411                 | 102                      | 432                 | 33           | 2.64         | 1.39              |
| 81918          | 39     | 0.16                   | 12492                 | 102                      | 418                 | 33           | 2.64         | 1.28              |
| 82209          | 41     | 0.15                   | 12422                 | 102                      | 418                 | 33           | 2.58         | 1.30              |

### Table 3  Engine conditions @ sampling for Oceania Vessel 6 (OV6)

| Total Eng. Hrs. | Temp C | Scav. Air Press. (bar) | Power @ sampling (kW) | Main Eng. RPM @ sampling | Consumption Ltr/day | BN (Used Oil) | Fuel Sulfur % | Cal. Feed Rate g/kWh |
|----------------|--------|------------------------|-----------------------|--------------------------|---------------------|--------------|--------------|-------------------|
| 71639          | 43     | 0.14                   | 8474                  | 100                      | 384                 | 43           | 3.03         | 1.77              |
| 72065          | 42     | 0.14                   | 8532                  | 101                      | 384                 | 54           | 3.03         | 1.76              |
| 72471          | 34     | 0.14                   | 8551                  | 100                      | 384                 | 47           | 3.04         | 1.75              |
| 72722          | 42     | 0.14                   | 8534                  | 100                      | 384                 | 45           | 3.04         | 1.75              |
| 81329          | 38     | 0.17                   | 8685                  | 101                      | 360                 | 39           | 2.64         | 1.16              |
| 81676          | 39     | 0.16                   | 8639                  | 100                      | 360                 | 42           | 2.64         | 1.21              |
| 81918          | 41     | 0.17                   | 8690                  | 101                      | 336                 | 33           | 2.58         | 1.51              |
| 82430          | 41     | 0.17                   | 8726                  | 101                      | 360                 | 35           | 2.58         | 1.61              |

### Table 4  Engine conditions @ sampling America Vessel 1 (AV1)

| Total Eng. Hrs. | Temp C | Scav. Air Press. (bar) | Power @ sampling (kW) | Main Eng. RPM @ sampling | Consumption Ltr/day | BN (Used Oil) | Fuel Sulfur % | Cal. Feed Rate g/kWh |
|----------------|--------|------------------------|-----------------------|--------------------------|---------------------|--------------|--------------|-------------------|
| 113338         | 39     | 0.10                   | 9727                  | 105                      | 442                 | 60           | 2.64         | 1.77              |
| 114117         | 26     | 0.20                   | 9878                  | 106                      | 431                 | 50           | 3.03         | 1.70              |
| 114798         | 35     | 0.20                   | 10029                 | 106                      | 432                 | 50           | 2.69         | 1.70              |
| 115813         | 42     | 0.20                   | 9887                  | 106                      | 431                 | 51           | 1.88         | 1.68              |
| 118432         | 28     | 0.20                   | 9632                  | 105                      | 432                 | 52           | 1.90         | 1.75              |
| 119641         | 36     | 0.20                   | 9321                  | 105                      | 425                 | 62           | 2.96         | 1.78              |
| 124056         | 37     | 0.20                   | 10570                 | 104                      | 410                 | 55           | 1.83         | 1.51              |
| 125347         | 31     | 0.20                   | 10570                 | 104                      | 411                 | 55           | 2.76         | 1.52              |
2.3 Cylinder oil and Fuel oil specification

In 2-stroke slow speed diesel engine internal combustion needs cylinder oil for lubricating liner walls due to long stroke and different from system oil for crankshaft lubrication. The CLO used during period of monitoring subject engines have maximum base number of 70 mg KOH/g and its specification is as follow in Table 6.

The engine is design with diaphragm and stuffing boxes to separate cylinder oil from mixing with crankshaft system oil, making it possible to independently lubricate crankshaft with system oil separately and cylinder liners and piston rings with CLO. The diaphragm prevents CLO from mixing with crankcase system oil, which give it independent to verify metallic debris in used scrape down CLO. The Table 6 indicates chemical properties of CLO use onboard for the ships for main engine.

Due to severe contamination from fuel oil and engine long stroke design, CLO characteristics are extreme important for lubrication of piston rings with cylinder liners. Therefore CLO must have sufficient viscosity, oxidation and thermal stability, demulsibility, rust and corrosion prevention, antifoaming, detergency, withstand extreme pressure in performance and biocides.

Table 7 is the International Standard Organization (ISO) basic specification for fuel oil that is compatible and burnable to all type of marine slow speed engine international marine law.

3. Results

A number of parameters were monitored during the course of monitoring subject ships, these include engine temperature, scavenger air pressure, max power at sampling, RPM, CLO consumption rate, BN of scrape down CLO, fuel oil sulfur percentage and CLO feed rate. To harmonize engine conditions at sampling of drain oil, samples will be taken when engine is 100rpm above. The drain CLO sample was analyzed using JOEL X-ray fluorescence equipment model number JSX-3100RII in 30kV tube and collimator of 7mm to count amount of metal particles found in the oil samples at rate of 100 seconds in air.

Figs. 1 and 2 represent residual BN of CLO against total engine operating hours. It is observed that America ships in Fig. 2 has large portion of residual alkali in drain CLO than Oceania ships using more portion of alkali in CLO as shown in Fig. 1. In Fig. 3 shows iron (Fe) debris for both American and Oceania ships. However, Oceania ships do show high quantity of Fe in comparison with America ships. Iron element is primary in manufacturing of cylinder.
liners materials in the composition.

Fig. 4 showed that about the same amount of Sulfur contents in marine fuel oil was utilized by both routes. Combustion fuel oil will produce acidic sulfide that elevate corrosion risk of cylinder liner. All subject engines make use of fuel oil containing sulfur ranges from 3.00%wt to max of 3.50%wt. Vanadium and Copper elements varies as indicated in Figs. 5 and 6 respectively, as copper element is used in manufacturing of piston rings plating. High amount of vanadium indicate incomplete combustion of fuel oil injected and cause high amount of iron wear in cylinder drain oil. The amount of Vanadium and copper elements from Oceania ships are scattered and spread on the graph that indicated that high rate of wear is occurring for these ships.
To limit contact between cylinder liners and piston rings, it is largely depend on CLO qualities. It is known that cold corrosion is caused by the amount of alkali on cylinder liner surface that react with sulfur producing acidic compound which increase risks of corrosive wear as indicated in equation (3) and equation (4).

4. Discussion

Two-stroke slow speed marine diesel engine makes use of turbochargers, scavenge air cooler with air receiver, an exhaust manifold and auxiliary blowers \(^{7}\) when engine running. The equipment are critical to starting, running and performances of an engine. Condition base monitoring (CBM) of cylinder liners management based on their sailing environment will improve utilization of CBM on maintenance policy. Base on subject engines we monitored, maintenance schedule or risk factors of sudden mechanical failure of engine can be narrow to environment of ship sailing route. The focus cylinder liner wears mechanical that influence by humid air from sea. Turbocharger in-let air is mostly from seawater containing water vapor. Sea-air contains contaminants that can facilitate corrosion and rusting of engine journal bearings \(^{8}\). Turbochargers conditions have significant effect on cylinder liners when it is inefficient, the side effect on engine performance can lead to higher exhaust gas temperature, lower charging pressure and smaller air mass flow causing chemical in-balance of combustion reaction. The in-take air compression is directly proportional to in-take temperature of turbochargers, when sailing in humid environment air containing water molecule will react with sulfur compound to produce acidic form sulfide.

Thermodynamic mechanism of 2-stroke slow speed engine begin by compressing air; compressed air will become hotter and sequentially cool down by scavenger cooler. The cool compressed air will abate excessive temperature on cylinder liners, also mixing with atomized fuel oil and CLO for combustion. Given that air large volume of air in-take for ignition and combustion, air quality is important in combustion process. Cylinder liners wall health monitoring will be affected by ocean air, which is reach in moisture and water molecule. Humidity percentage in-take air varies depending on environment of ship sailing sea.

CBM on cylinder liners make use of residual BN and Fe wear found in drain CLO samples. When CBM is model according to their sailing environment, maintenance decision will be enhanced and swift to maximize output performance of engine. Also CBM will improve predicting cylinder liners remain life in operation, especially when affected by cold corrosion \(^{13}\). This phenomenon may associate with ships sailing to Oceania ports. These Oceania ships generating more of iron metal in their scrape down CLO.

CLO contains additive of CaCO\(_3\) that supposed to neutralize acid and formed CaSO\(_4\) as in equation (5). However, when neutralization reaction do not occurred Fe react with sulfuric acid to produce FeSO\(_4\) as in equation 6 that solidify into larger particles scuffing cylinder liner wall leading to increase wear of Fe element in drain CLO.

\[
\begin{align*}
\text{H}_2\text{SO}_4(aq) + \text{CaCO}_3(s) &\rightarrow \text{CaSO}_4(s) + \text{H}_2\text{O}(l) + \text{CO}_2(g) \quad (5) \\
\text{Fe}_o + \text{H}_2\text{SO}_4(aq) &\rightarrow \text{FeSO}_4(aq) + \text{H}_2(g) \quad (6)
\end{align*}
\]

5. Conclusion

There is no doubt that from the results of monitored ships condition based monitoring (CBM) that include environment of sailing in the approach will be important in management and maintenance of slow speed 2-stroke diesel engine facing different environmental challenges. As different amount of water molecule quantity in air from sailing environment can have adverse effect on combustion of fuel oil and result to increase amount of wear between piston rings and cylinder liners. CBM model that is tailored to the environment of sailing pattern will be beneficial to maintenance policy on engine. And maintenance policy that includes as-frequent-as-possible and run-to-failure method can be improved in their application on managing 2-stroke slow speed engine.

Conflict of Interest

The authors declare no conflict of interest.

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