Remarks on the Automatic Cylinder Oil Mixing System for Two Stroke Dual Fuel Crosshead Marine Engines

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INTRODUCTION

Commissioning and operation of first two stroke, dual fuel (Diesel Cycle) engines is one of the most important part of the marine engine rooms operation (Nozdrzykowski, 2006, 2018; Nozdrzykowski and Bejger, 2013; Nozdrzykowski and Janecki, 2014; Nozdrzykowski, Grządziel and Harušinec, 2018; Nozdrzykowski and Chybowski, 2019). It revealed whole gamut of new problems that presented operators with potential for increased wear of the liners, piston rings and pistons (Gawdzińska, Chybowski and Przetakiewicz, 2017; Gawdzińska et al., 2018, 2019) which is directly related to type of fuel used and its Sulphur content (Antturi et al., 2016; Chu Van et al., 2019; Wang, Zhang and Gan, 2019). Sulphur is neutralized with, available commercially from 1950's, high alkalinity cylinder oils. Problems arise during fuel changeover, which also requires change of cylinder lubricating oil base number (CLO BN). Sulphur limit in marine fuels has been introduced with MARPOL Annex VI – Fuel Sulphur Limits (Fig. 1).

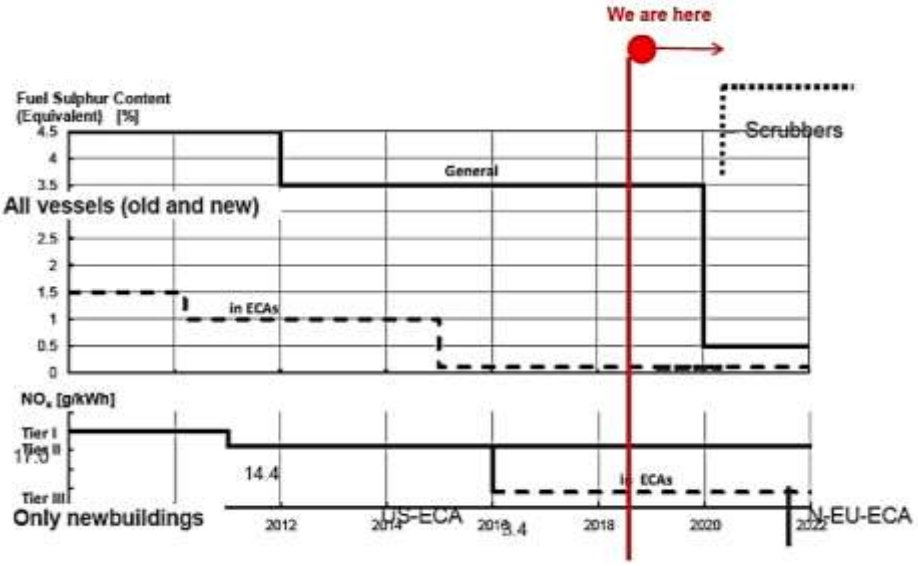

Fig. 1 Fuel Sulphur Cap

Source: (MAN Diesel & Turbo, 2018)

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Geographically, it is defined by boundaries of vessel operations which are called Sulphur Emission Control Area (SECA) (Laskowski, Chybowski and Gawdzińska, 2015; Chybowski et al., 2016). Location of this areas is presented in Figure 2. Further, final change to the Sulphur cap has been introduced at 1st of January 2020, where maximum Sulphur content in marine fuel was reduced from 3.5% to 0.5%

Fig. 2 SECA + NECA

Source: (MAN B&W Diesel A/S, 2013)

CAUSES AND EFFECTS OF INCORRECT CLO DOSING

Cylinder liner damage or increased wear has its source in eithe under or overlubrication. Correct dosing depends on amount of Sulphur in the fuel oil as well as engine load (including power optimisation in the form of Exhaust Gas Bypass and Turbocharger cut out. This in turn sets the required amount of alkali additives (Fig. 3).

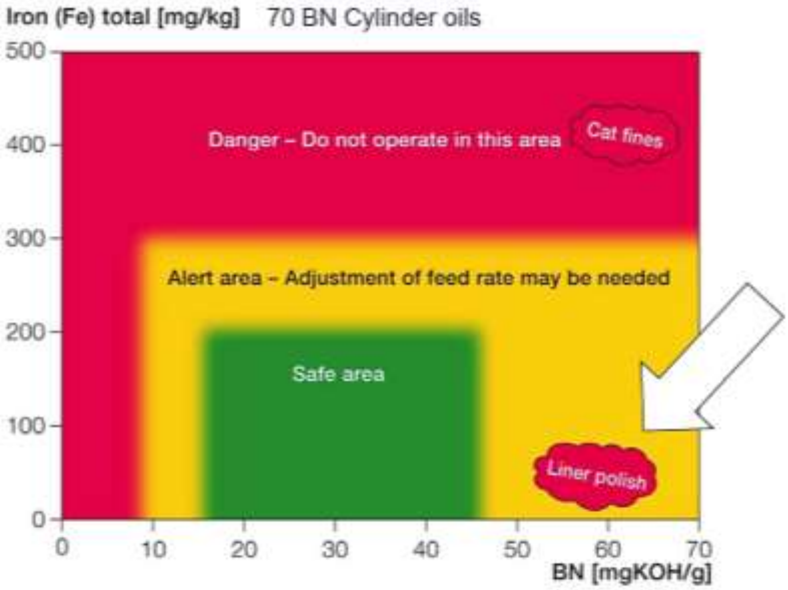


Fig. 3 Liner Lubrication

Source: (MAN B&W Diesel A/S, 2013)

Base Number (BN) is a measure of oil's ability to neutralise sulphuric acid on the cylinder liner surface. Corrosion has to be controlled and is extremely important in the tribology required to establish and retain oil film on the surface of the liner. With too much BN and subsequently over neutralisation, surface of the liner will be polished, which will result in disruption to the friction and increased risk of damage to liner surface and piston rings (Fig. 4). Too low BN value will result in insufficient neutralisation and significant risk of low temperature sulphur-based corrosion.

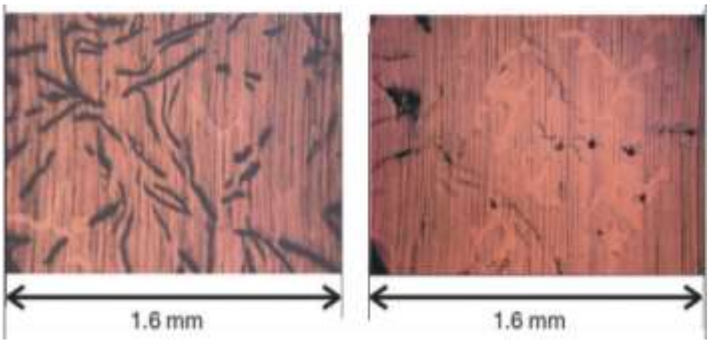


Fig. 4 Open (L) and closed (R) structure of the liner surface

Source: (MAN Diesel & Turbo, 2018)

Sulphuric acid is being produced during combustion of fuels containing sulphur. It may liquefy on the liner surface – this is due to presence of water in the scavenge air and thermodynamics of combustion, when temperature and pressure creates atmosphere which is below dew point of SO_3 (Fig. 5).

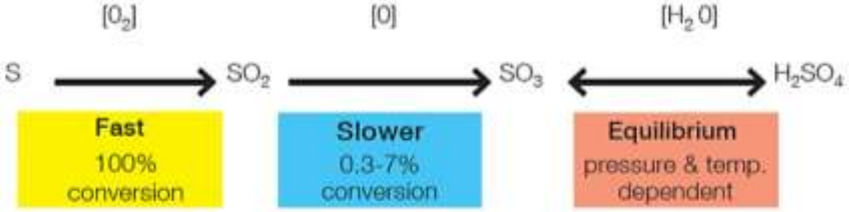


Fig. 5 Conversion of S to H_2SO_4

Source: (MAN Diesel & Turbo, 2018)

With inadequate neutralisation, level of iron in the cylinder oil will increase. According to MAN Diesel & Turbo, level of 200 mg/Kg corresponds to nominal wear of the cylinder liner and equals 0.1 mm/1000 Running Hours (RH) (Fig. 3). Therefore, higher values will indicate increased wear of the liners, rings and ultimately pistons.

Total amount of the alkali additives must correspond to the Sulphur content according to the equation below:

$$BN = FRF \times S\% \qquad (1)$$

where:

FRF for CLO BN100 (high BN, liquid fuel) = 0.40 g/kWhS%

And for CLO BN40 (low BN, methane fuel) – 0.25 g/kWhS%.

MAN sets the minimum specific CLO feedrate at 0.6 g/kWh, which will be achieved with fuel that contains 1.15% of Sulphur, using CLO BN100. This sets the theoretical limit for use of BN100 CLO at 1.15%S.

With use of CLO BN40 (utilised during methane operations) 0.6 g/kWh limit does not allow for BN – S equilibrium (Fig. 6).

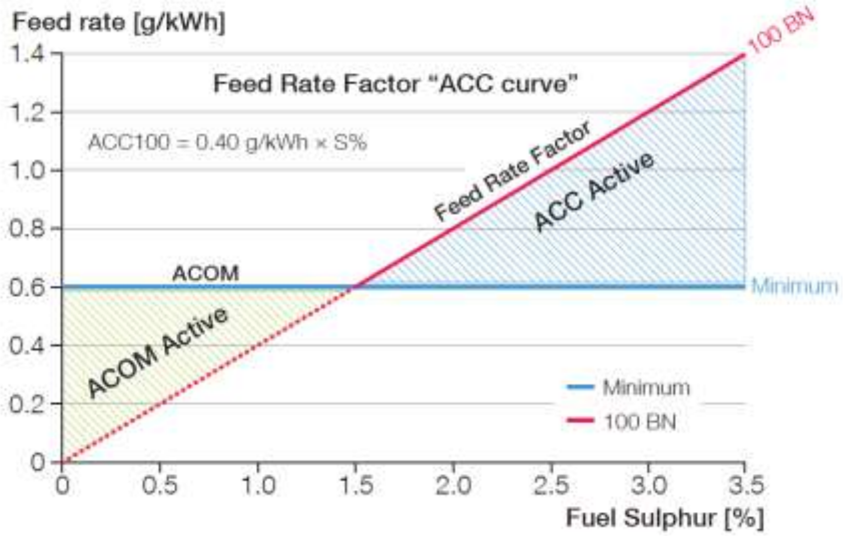


Fig. 6 ACC Area (feed rate factor) for CLO BN100 used in Mark 8-8.1 and newer engines
Source: (MAN Diesel & Turbo, 2015)

MEGI engines cannot be run in gas mode at low loads (< = 20). This is due to physical size of the fuel injectors, which also serve as pilot ones.

It is therefore obvious that operation of the engine with low sulphur fuel will be much more complicated due to relationship between liner surface corrosion and its resistance to friction wear and also between BN of the CLO, its detergency and possible surplus of the alkali additives. (Chybowski, Laskowski and Gawdzińska, 2015)

Toprecisely determine scale of the neutralisation process and therefore the physical and chemical attributes of used CLO, oil must be removed from the engine during Sweep Test (Fig. 7). Test is being carried out by sampling cylinder drains at predefined time and at various specific feed rates.

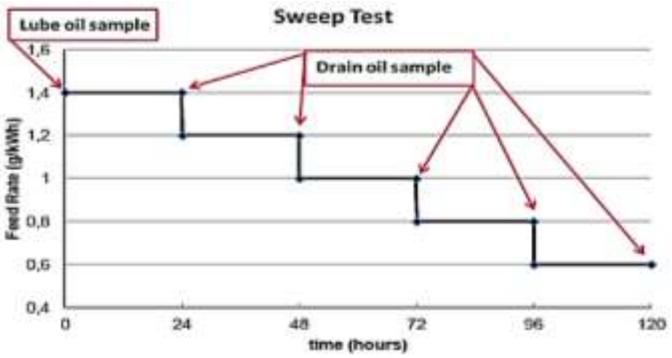


Fig. 7 Sweep Test
Source: (MAN Diesel & Turbo, 2018)

Measuring iron and residual BN contents will allow for a very precise assessment of the liner condition as well as need of adjustment to feed rate if required to move back in to safe area (Fig. 8). It must be noted, that Sweep Test should only be carried out with fuels that contain higher amounts of Sulphur. Otherwise, results may not be precise enough, or much longer time will be required to complete the test. Operator, should also ensure that engine load is relatively steady during the test.

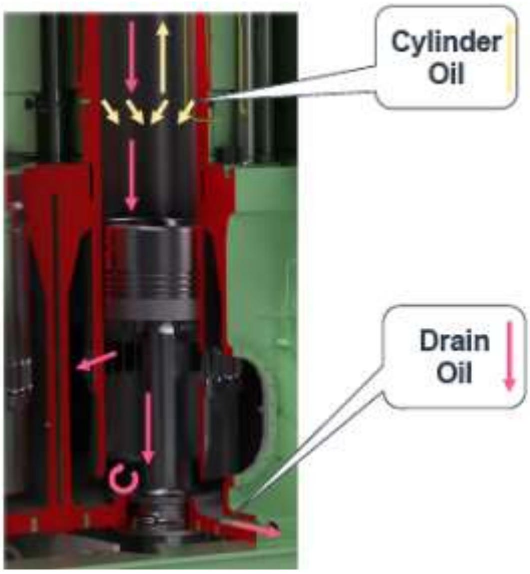


Fig. 8 Cylinder Oil Flow

Source: (MAN Diesel & Turbo, 2018)

Insufficient lubrication (underlubrication), invariably leads to excessive wear / damage both to surface of the cylinder liner as well as piston rings, due to increased corrosion and lower overall detergency of the cylinder oil being admited to the unit. Cold corrosion becomes reality and is likely to happen. Engine is in danger of underlubrication in high load band only, this is due to activation of LCD at loads below 25% of MCR. Operating LCD increases CLO feedrate by 25% and thus protects running gear from underlubrication.

Too much cylinder oil will lead to overlubrication, which in time will cause for surface structure to close (Fig. 8) and subsequenty occurence of bore polishing. Noted will be increased amount of unused alkali additives, which may cause problems with Tier III equipment further down the line. For example, operation of the engine EGR system will be affected due to need for removal of alkali solids and lack of pH equilibrium in the primary (air cooler – buffer tank) circuit.

INCORRECT LUBRICATION PREVENTION

Based on the above rationale, it becomes apparant that there is a need for use of two cylinder oils, differentiated by Base Number (BN).

Point of switch is based solely on the experience gained during first days and weeks after the delivery (Fig. 9).

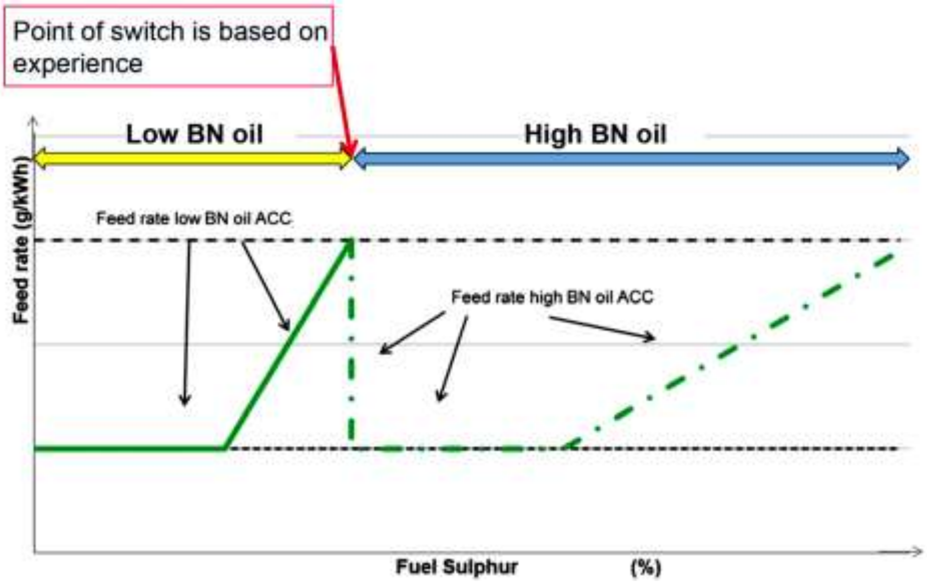


Fig. 9 Cylinder oil changeover
Source: (MAN Diesel & Turbo, 2018)

Sweep Test will allow for correct setting of the FRF for high sulphur fuel and frequent, detailed scavenge space inspections will provide experience required to establish correct BN for use with methane fuel.

Automatic Cylinder Oil Mixing (ACOM)

ACOM is the newest solution currently in use with MEGI Power Plants (Fig. 10). System allows for cylinder oil mixing and dosing in relation to engine load and type of fuel used.

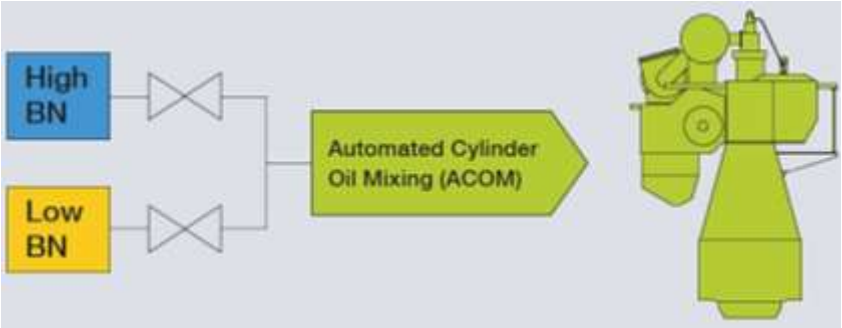


Fig. 10 Automated Cylinder Oil Mixing
Source: (MAN Diesel & Turbo, 2018)

ACOM also allows for dosing engines operating in specific dual fuel mode (SDF) – which defines relationship between pilot and gas fuel. It is a very important feature of the MEGI engine and utilised when engines are part of the tank pressure control and / or when plant is being operated with heel. ACOM mixes two, different BN, oils into the one with requested BN value. Currenly BN 100 and BN16 are utilised as a base oils. This creates a very ‘flexible’ environment, where all the currently used BN values (including exotic ones) are available. ACOM is controlled with the engine ECS (Fig. 11) allowing for it’s continuous monitoring. All the adjustments can be carried out through MOP and/or ACOM digital panel. Hardware itself is of quite small footprint and consists of relatively small number of parts.

Fig. 11 Automated Cylinder Oil Mixing Unit on the skid

Source: (MAN Diesel & Turbo, 2018)

Figure 12 describes typical ACOM control panel in the MOP. It consists of functions as per below:

- High BN Value – BN value setting for high Sulphur fuel.
- Low BN Value – BN value setting for low Sulphur/gas fuel.
- Feed Rate Factor – value optained during the Sweep Test.
- Engine Mean Effective Pressure given in percent at which LCD algorithm changes in to RPM mode.
- Minimum feedrate – minimum, specific CLO dose delivered to the engine in the RPM algorithm band.

Therefore, the biggest challenge faced by the operator will be to ensure CLO contain correct amount of BN additives when engine is being operated with low sulphur fuel.

Lets assume that: Engine operates in HFO mode with liquid fuel consisting of 1.8% of Sulphur.

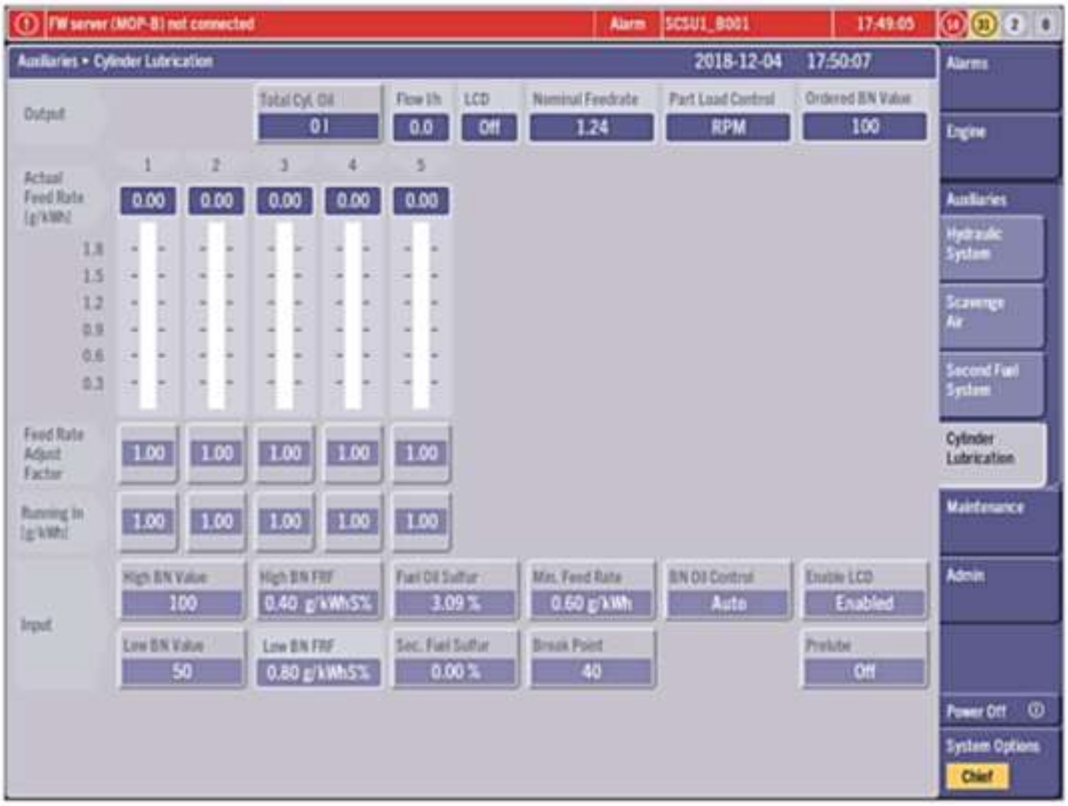
ACC Feed rate factor = 0.25 g/kWh x S% (established during sweep test).

Minimal specific CLO feedrate = 0.6 g/kWh,

therefore:

calculated minimal specific CLO feedrate = 0.25 x 1.8 = 0.45 g/kWh.

Value of 0.45 g/kWh is below minimal feedrate. ECS therefore will request 0.6 g/kWh. Sulphuric acid may be then completely neutralised, increasing risk of bore polishing and thus increased wear.



FW server (MOP-B) not connected | Alarm | SCSU1_B001 | 17:49:05

Auxiliaries • Cylinder Lubrication 2018-12-04 17:50:07

Output

Total Cyl. Oil: 0 l
Flow l/h: 0.0
LCD: Off
Nominal Feedrate: 1.24
Part Load Control: RPM
Ordered BN Value: 100

	1	2	3	4	5
Actual Feed Rate [g/kWh]	0.00	0.00	0.00	0.00	0.00
Feed Rate Adjust Factor	1.00	1.00	1.00	1.00	1.00
Running In [g/kWh]	1.00	1.00	1.00	1.00	1.00

Input

High BN Value: 100
High BN FRF: 0.40 g/kWhS%
Fuel Oil Sulfur: 3.09 %
Min. Feed Rate: 0.60 g/kWh
BN Oil Control: Auto
Enable LCD: Enabled
Low BN Value: 50
Low BN FRF: 0.80 g/kWhS%
Sec. Fuel Sulfur: 0.00 %
Break Point: 40
Prelube: Off

Fig. 12 ECS MOP Cylinder Lubrication page

Source: Authors own

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Value of 0.45 g/kWh is below minimal feedrate. ECS therefore will request 0.6 g/kWh. Sulphuric acid may be then completely neutralised, increasing risk of bore polishing and thus increased wear.

Correct dose will call for oil with reduced Base Number.

Therefore:

Minimum Feed rate/fuel S% = FRF

0.6/1.8 = 0.33 (optimal FRF)

FRF for BN 100 = 0.25.

$$\mathrm{FRF100} = \mathrm{FRF70}\ \mathrm{x}\ \frac{70}{100} \rightarrow \mathrm{FRF100} = \mathrm{FRFop}\ \mathrm{x}\ \frac{\mathrm{BNop}}{100} \rightarrow \mathrm{BNop} = \frac{\mathrm{FRF100}}{\mathrm{FRFop}}\ \mathrm{x}\ 100$$

Optimal BN for FRF 0.33 equals to

$$\frac{0.25}{0.33}\ \mathrm{x}\ 100 = \mathbf{76BN}$$

Setting of 76BN will allow for correct dosing at minimal feedrate of 0.6 g/kWh.

MATERIALS AND METHODS

Feed rate factor has been established through sweep test carried out on MAN-B&W/5G70ME-C9.5-GI engine operating on HFO with Sulphur content of 2.97%. Test has taken place over five days and was carried out under conditions as laid in MAN SL2014-587:

- Engines loaded above the LCD breakpoint
- Running in Mode off
- Feed Rate Adjust Factor = 1.00
- Feed Rate set to:
- 1.38 g/kWh for first sweep
- 1.24 g/kWh for second sweep
- 1.00 g/kWh for third sweep
- 0.87 g/kWh for fourth one and
- 0.64 g/kWh for the fifth.

ACC factor has been established according to the formula below:

$$\mathrm{ACC}_{\mathit{Calculated}}\left[\frac{g}{kWh\ x\ S\%}\right] = \frac{Feed\ rate\ [\frac{g}{kWh}]}{Fuel\ Sulphur\ [S\%]}$$

RESULTS AND DISCUSSION

Data had been referenced to engine running hours, engine load and elemental analysis carried out on collected samples (Table 1, 2, 3, 4, 5). Note cylinder unit No. 2 which drain was found blocked on 18th of November.

Below values were obtained:

Correction for system oil dilution

■ – corrected

□ – not corrected

Table 1 Sweep Test Results FR 1.38 g/kWh, Castrol Caremax Cylinder Oil Monitor

CYLINDER UNIT	N°	**1**	**2**	**3**	**4**	**5**
PISTON HOURS SINCE OVH	Hrs	560	560	560	560	560
CYLINDER OIL FEED RATE	g/kWh	1.38	1.38	1.38	1.38	1.38
CYLINDER OIL	CYLTECH 100					

■	DURING SAMPLING % MCR		75.7	% S in Fuel	2.97	Load (kW)	10200	Engine Hours	570	Feed rate	1.38
		Date Sample Taken		14.11.18	14.11.18	14.11.18	14.11.18	14.11.18	The analysis results, based on the tests performed, indicate that an overall satisfactory condition for all units. There is a high BN reserve across all units. Cu content across all units is likely to reflect the running in of the Alucoat piston rings.		
LATEST CYLTECH 100	□	Base Number □	mgKOH/g	57.9	58.4	55.9	63.6	59.9			
	■	Base Number ■	mgKOH/g	68.1	64.8	66.1	69.8	65.2			
		Total Water	5vol	0.75	0.68	0.64	0.64	0.62			
	□	Iron (Fe) □	ppm	115	119	111	131	149			
	■	Iron (Fe) ■	ppm	137	133	133	145	163			
	□	MFA	ppm	136	146	141	153	121			
	■	Lead (Pb)	ppm	2	2	3	3	2			
	■	Copper (Cu)	ppm	58	62	50	71	39			
	■	Aluminum (Al)	ppm	17	18	17	20	19			
	■	Chrome (Cr)	ppm	2	2	5	6	5			
	■	Molybdenum (Mo)	ppm	8	9	7	10	11			
	■	Silicon (Si)	ppm	54	53	52	57	60			
	■	Nickel (Ni)	ppm	116	114	107	132	140			
	■	Vanadium (V)	ppm	411	408	373	451	491			

Table 2 Sweep Test Results FR 1.22 g/kWh, Castrol Caremax Cylinder Oil Monitor

CYLINDER UNIT	N°	1	2	3	4	5
PISTON HOURS SINCE OVH	Hrs	590	590	590	590	590
CYLINDER OIL FEED RATE	g/kWh	1.22	1.22	1.22	1.22	1.22
CYLINDER OIL	CYLTECH 100					

■	DURING SAMPLING % MCR		77	% S in Fuel	2.97	Load (kW)		Engine Hours	589	Feed rate	1.22
		Date Sample Taken		15.11.18	15.11.18	15.11.18	15.11.18	15.11.18	The analysis results, based on the tests performed, indicate an increase in Fe content on some cylinder units suggesting oil feed rate could be below optimal settings for certain combinations of fuel specification / engine load. The wear is predominantly of the corrosive type, reserve BN is high across all units. Cu content across all units is likely to reflect the running in of the Alucoat piston rings.		
LATEST CYLTECH 100	□	Base Number □	mgKOH/g	46.3	43.7	54.2	51.4	53.1			
	■	Base Number ■	mgKOH/g	55.1	50.5	65.9	55.5	57.7			
		Total Water	5vol	0.67	0.73	0.62	0.69	0.61			
	□	Iron (Fe) □	ppm	154	149	150	160	220			
	■	Iron (Fe) ■	ppm	186	175	185	174	241			
	□	MFA	ppm	127	136	147	168	142			
	■	Lead (Pb)	ppm	2	4	3	2	3			
	■	Copper (Cu)	ppm	36	44	42	47	31			
	■	Aluminum (Al)	ppm	18	17	15	19	20			
	■	Chrome (Cr)	ppm	4	4	7	9	8			
	■	Molybdenum (Mo)	ppm	10	10	9	11	13			
	■	Silicon (Si)	ppm	51	48	44	54	57			
	■	Nickel (Ni)	ppm	140	127	106	143	162			
	■	Vanadium (V)	ppm	484	442	368	496	560			

Table 3 Sweep Test Results FR 0.97 g/kwh, Castrol Caremax Cylinder Oil Monitor

CYLINDER UNIT	N°	1	2	3	4	5
PISTON HOURS SINCE OVH	Hrs	613	613	613	613	613
CYLINDER OIL FEED RATE	g/kWh	0.97	1.22	0.97	0.97	0.97
CYLINDER OIL	CYLTECH 100					

■	DURING SAMPLING % MCR		81	% S in Fuel	2.97	Load (kW)		Engine Hours	613	Feed rate	0.97
		Date Sample Taken		16.11.18	16.11.18	16.11.18	16.11.18	16.11.18	The analysis results, based on the tests performed, indicate a significant increase in Fe content across all cylinder units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load. The wear is predominantly of the corrosive type, reserve BN is high across all units. Cu content across all units is likely to reflect the running in of the Alucoat piston rings.		
LATEST CYLTECH 100	□	Base Number □	mgKOH/g	28.4		31.4	31.7	32			
	■	Base Number ■	mgKOH/g	35.2		41.4	35.5	36.9			
		Total Water	5vol	0.64		0.56	0.7	0.61			
	□	Iron (Fe) □	ppm	390		376	397	431			
	■	Iron (Fe) ■	ppm	390		376	397	431			
	□	MFA	ppm	139		141	152	166			
	■	Lead (Pb)	ppm	2		2	3	4			
	■	Copper (Cu)	ppm	37		39	55	31			
	■	Aluminum (Al)	ppm	18		15	23	22			
	■	Chrome (Cr)	ppm	7		8	12	13			
	■	Molybdenum (Mo)	ppm	14		11	16	18			
	■	Silicon (Si)	ppm	51		43	56	58			
	■	Nickel (Ni)	ppm	155		117	179	190			
	■	Vanadium (V)	ppm	534		398	609	660			

Table 4 Sweep Test Results FR 0.86 g/kWh, Castrol Caremax Cylinder Oil Monitor

CYLINDER UNIT	N°	1	2	3	4	5
PISTON HOURS SINCE OVH	Hrs	613	613	613	613	613
CYLINDER OIL FEED RATE	g/kWh	0.97	1.22	0.97	0.97	0.97
CYLINDER OIL	CYLTECH 100					

■	DURING SAMPLING % MCR		75	% S in Fuel	2.97	Load (kW)		Engine Hours	■	Feed rate	0.97
		Date Sample Taken		17.11.18	17.11.18	17.11.18	17.11.18	17.11.18	The analysis results, based on the test performed, indicate a significant increase of Fe content across all units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load, the wear is predominantly of the corrosive type. The reserve BN across all units is approaching the below safe margin.		
LATEST CYLTECH 100	□	Base Number □	mgKOH/g	15.4		19.5	17	20.6			
	■	Base Number ■	mgKOH/g	21.1		24.8	21.1	24.6			
		Total Water	5vol	0.63		0.67	0.58	0.66			
	□	Iron (Fe) □	ppm	386		510	579	538			
	■	Iron (Fe) ■	ppm	609		701	784	681			
	□	MFA	ppm	151		187	199	194			
	■	Lead (Pb)	ppm	4		3	4	4			
	■	Copper (Cu)	ppm	37		46	68	40			
	■	Aluminum (Al)	ppm	20		20	26	29			
	■	Chrome (Cr)	ppm	9		13	18	18			
	■	Molybdenum (Mo)	ppm	17		19	20	25			
	■	Silicon (Si)	ppm	47		49	56	66			
	■	Nickel (Ni)	ppm	169		161	204	255			
	■	Vanadium (V)	ppm	596		574	705	875			

Table 5 Sweep Test Results FR 0.63 g/kWh, Castrol Caremax Cylinder Oil Monitor

CYLINDER UNIT	N°	1	2	3	4	5
PISTON HOURS SINCE OVH	Hrs	660	660	660	660	660
CYLINDER OIL FEED RATE	g/kWh	0.63	1.22	0.63	0.63	0.63
CYLINDER OIL	CYLTECH 100					

	DURING SAMPLING % MCR		79	% S in Fuel	2.97	Load (kW)		Engine Hours		Feed rate	0.97
		Date Sample Taken		18.11.18	18.11.18	18.11.18	18.11.18	18.11.18			
LATEST CYLTECH 100	□	Base Number □	mgKOH/g	9.8		11.9	12.7	16.4	The analysis results, based on the test performed, indicate a significant increase of Fe content across all units suggesting oil feed rate is below optimal settings for certain combinations of fuel specification / engine load, the wear is predominantly of the corrosive type. The reserve BN across all units is approaching the below safe margin.		
	■	Base Number ■	mgKOH/g	12.5		15.4	16.5	24.6			
		Total Water	5vol	0.54		0.49	0.44	0.66			
	□	Iron (Fe) □	ppm	431		566	653	538			
	■	Iron (Fe) ■	ppm	709		878	996	681			
	□	MFA	ppm			119	180	194			
	■	Lead (Pb)	ppm	3		1	2	4			
	■	Copper (Cu)	ppm	32		39	61	40			
	■	Aluminum (Al)	ppm	25		22	30	29			
	■	Chrome (Cr)	ppm	15		15	21	18			
	■	Molybdenum (Mo)	ppm	23		22	28	25			
	■	Silicon (Si)	ppm	51		48	59	66			
	■	Nickel (Ni)	ppm	225		190	252	255			
	■	Vanadium (V)	ppm	761		638	842	875			

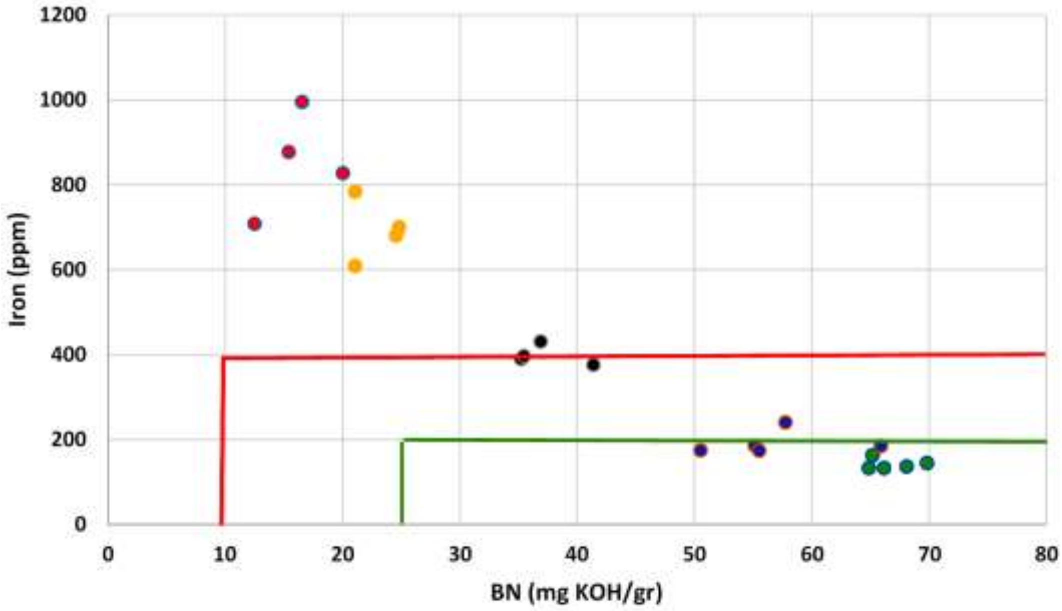

Fig. 13 Scatter graph of the values obtained through five days of sweep test (green line – normal limit, red line – warning)

Source: (Castrol, 2020)

Analysis of the sweep test results indicate feed rates of 1.38 g/kWh and 1.22 g/kWh as close to optimal for HFO with Sulphur content of 2.97. Any further reduction will increase risk of corrosive wear.

However, legislative changes forced operators to use low Sulphur fuel only. This negates possibility of the corrosive wear, however, it does significantly increase risk of bore polishing. With low/no Sulphur fuels, the only way to ensure correct dosing is to change BN value through mixing unit.

Note that in dual fuel installation, fuel changeover will occur in two scenarios:

- Change from liquid fuel to gas, done at certain, predefined loads
- Change from gas to liquid fuel – achieved with preparation of the engine for low load operation, due to SECA requirement or due to operational problems

Therefore, it is of most importance to carry out frequent scavenge spaces inspections – this is in order to ensure polishing does not occur.

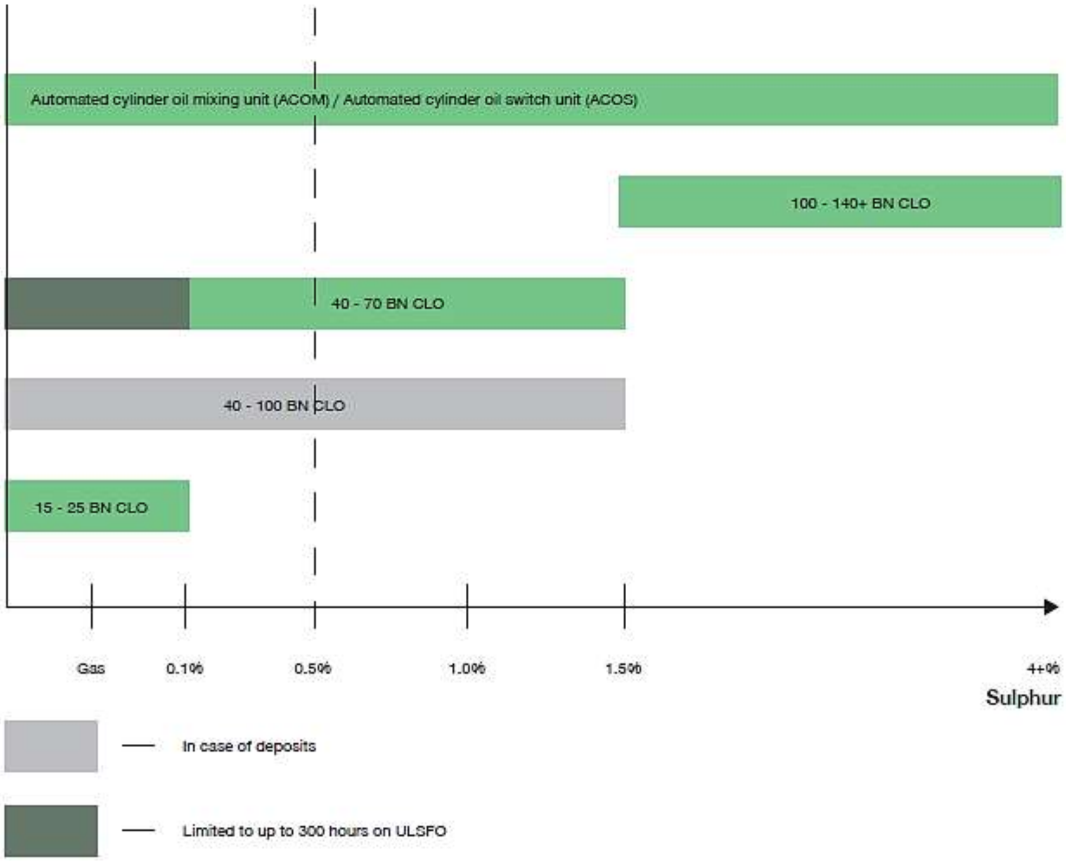

Fig. 14 Recommended BN levels for MAN B&W Engines

Source: (MAN Diesel & Turbo, 2019)

Based on experience gathered to date, BN value for gas operation is set at 40. This requires frequent inspections to be carried out as well as periodical operation on high BN oil (Cyltech 100).

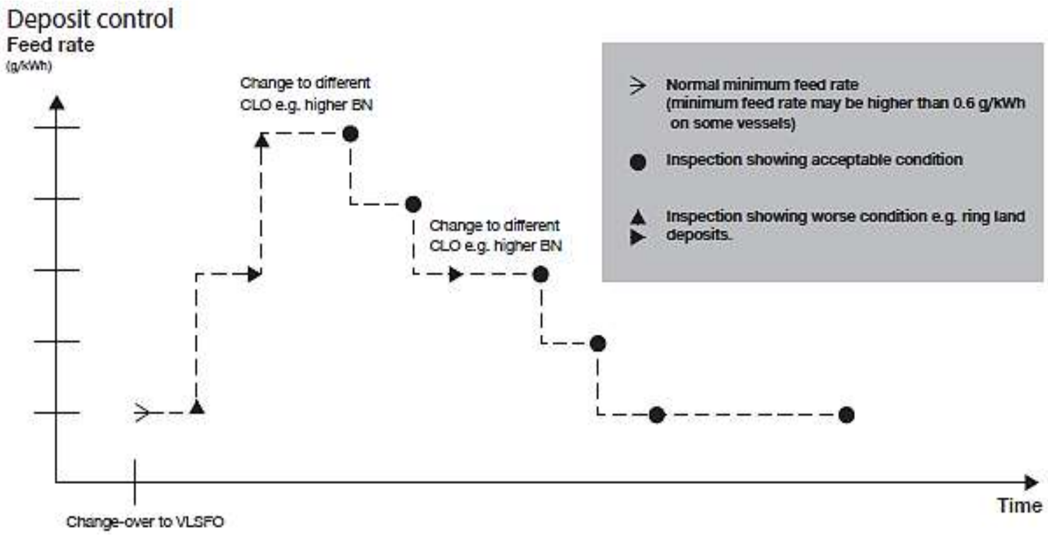

Fig. 15 Deposit control

Source: (MAN Diesel & Turbo, 2019)

Figure 16 displays cylinder unit in excellent condition, operating in gas mode for over 10K running hours. Deposits on first ring land indicate a need for period of high BN operation. Trialled procedure calls for three days run with CLO 100 BN.

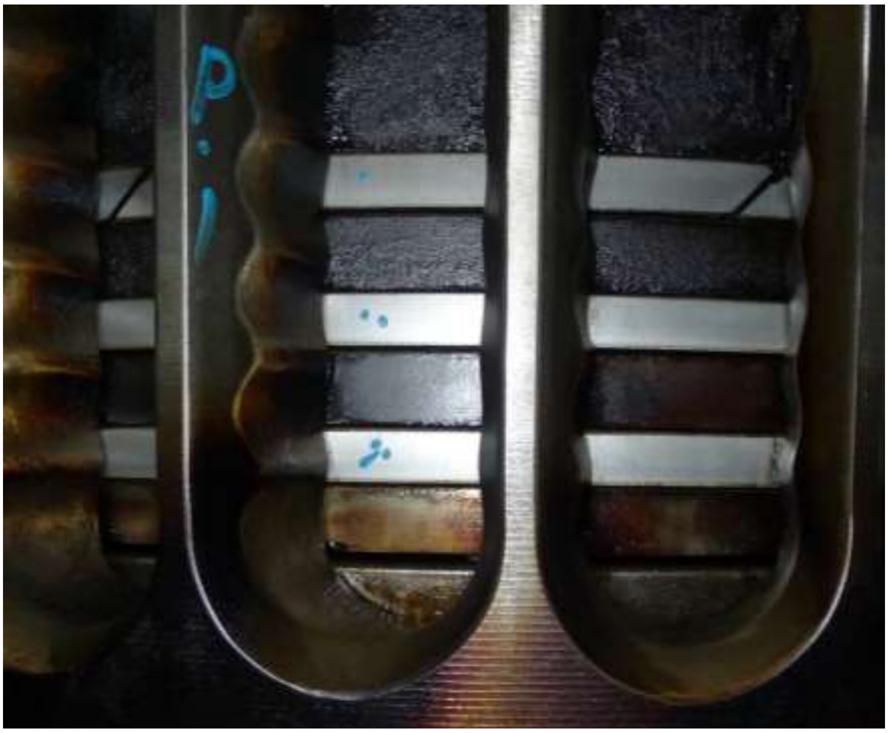

Fig. 16 Feed rate of 0.6 g/kWh with CLO BN 40

Source: Author's own Nov 2018

Figure 17 presents same unit, after high BN run. It is evident ring lands were cleaned out of all deposits.

Fig. 17 Feed rate of 0.6 g/kWh after 72 hours operation with CLO BN 100

Source: Author's own Nov 2018

CONCLUSION

Introduction of MARPOL Annex VI – Fuel Sulphur Limits, forced owners and operators to use various BN cylinder oils. It is therefore not possible to operate the engines within expected wear margins without continuous change to its operational parameters. To be able to adjust/change these parameters, marine engineer must understand the whole process of liner lubrication, which requires adjustment based on empirical data being gathered continuously through the vessel's life. Nothing will replace frequent scavenge spaces inspections as well as very close monitoring of feedrate and Base Number of the cylinder oil.

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Abstract: The deformation of a part occurring in the process of grinding directly influences its exploitation and quality parameters. The instability of shape and size, which occurs due to an imbalance of residual stress, can be the one of the major causes of deformation of a part. The decrease in stress slows down the deformation process. Considering the regularities of heat source intensity dependence on the grinding modes, it can be asserted that with increasing grinding depth and grinding wheel hardness, the value increases and it decreases with a growth in a speed of the part and the use of cooling. The higher the heat removal is and the better lubricant properties of the liquid are, the more significant the decrease in is. Changing these values allows regulation of the residual stresses. As a result of the research on determination of deformations, it is recommended to reduce thermal deformations by considering the geometric size of a plate to be machined, linear expansion coefficient of plate material and an allowance for nonflatness from thermal deformations. The value of nonflatness from thermal deformations is directly proportional to linear expansion coefficient of plate material and its square overall dimensions. At the same time, the value of nonflatness is inversely proportional to the plate thickness.

Keywords: deformation, stress state is determined, stress diagram, scheme of residual stress formation, grinding