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MODELING A PURIFICATION SYSTEM FOR EFFICIENT REMOVAL OF ABRASIVE IMPURITIES

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ABSTRACT

Aluminium and silicon particles in fuel known as “cat fines” are catalytic residues from the refinery process. They can cause mechanical damage to fuel pumps, injectors, piston rings and cylinder liners. They are very hard and highly abrasive, thus causing abrasive wear to main engine components. These impurities in marine fuel must be minimised to recommended levels. One of the main tasks of the fuel treatment plant on a ship is to separate solids and water from the fuel. Modern vessels are equipped with fuel separators which rotate at a high speed (more than 6,000 rev/min) producing centrifugal force and providing good separating effect even for small solid particles (Al+Si). Proper settling and regular drainage from the tanks, even when adequate filtration is applied, are not sufficient for proper fuel preparation. The quality of purifier operation varies over years because it is affected by a large number of factors. For the purpose of this paper, over twelve thousand fuel samples were analysed to determine the current efficiency of the purifiers and whether they can meet the stringent requirements of marine engine manufacturers. The data will be taken from a tanker ship, considering different operational scenarios. These scenarios are linked to the maximum possible fuel consumption on the ship during exploitation. Using the Simulink program for the system simulation, optimisation can be achieved in the operation of fuel separator. This optimization refers to the required amount of fuel and quality of separation, particularly concerning the removal of abrasive impurities.

Keywords: Abrasive wear, Cat fines, Purifier optimization, Ship automation & simulation.

INTRODUCTION

Modern ships in the merchant navy generally have two fuel separators, while passenger ships and ships powered by diesel electric can have one for each of the engines. The problem of catalytic impurities has not been a recent phenomenon. On the contrary, it dates back to the eighties of the last century. If these impurities enter the engine combustion chamber, the parts (surfaces) are prone to wear out. Additionally, cracks can occur in the cylinder liner and piston rings, which will cause a huge problem for the main engine.

Major marine engine manufacturers recommend that these impurities be less than 10 µm (Vukičević, Račić, & Ivošević, 2019). Nevertheless, if stuck in the cylinder liner or in the space between the groove of the ring and the piston ring itself, even a smaller amount of impurities along with poor lubrication can still lead to unwanted wear.

The costs that can arise in these situations range from several hundred thousand dollars to even over a million (Vukičević, Račić, & Ivošević, 2019). Therefore, it is necessary to develop a model that will credibly describe the given problem and indicate the way the process of fuel purification may be improved.

PROBLEMS WITH FUEL IMPURITIES AND PURIFIER EFFICIENCY (2018 - 2020)

The problems arising during fuel bunkering, fuel storage in the ship's tanks and during the entire process of entering the main engine are analysed here. The design of the tanks and the materials used for the construction will not be discussed because those would relate to increased investments by the company. Provided that fuel heating coils in the tanks work properly and that the engineers adjust the fuel temperature correctly, further improvement and upgrade of the system will not be the focus of our attention in this paper.

It should be noted that even when using very low sulphur fuel oil (VLSFO), problems can occur. In specific problems reported for marine fuel (Innospec technical bulletin [ITB], 2020), as many as 37% of cases are related to serious failures on the separators, along with other incidents reported during the use of the fuel. One of the problems leading to the wear of the surface layer on the cylinder liner was the one caused by cat fines.

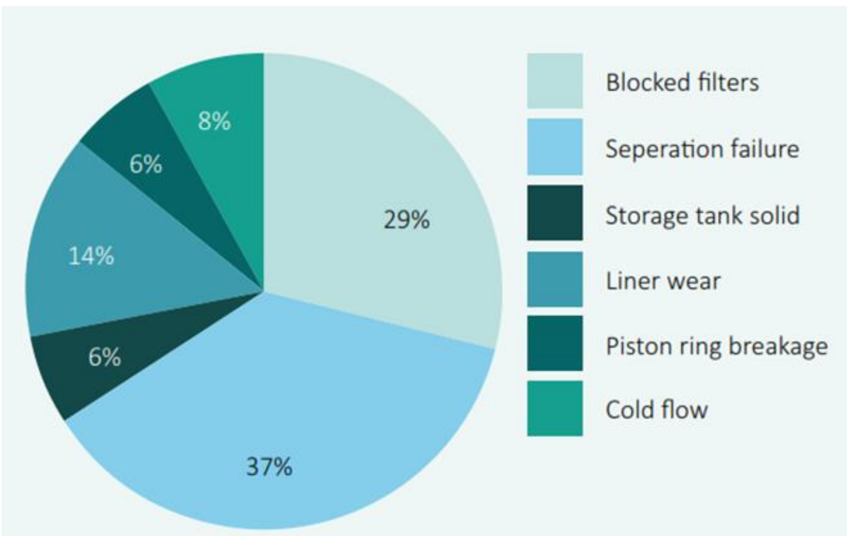

Figure 1 – The frequency of incidents experienced by vessels using VLSFO in Q1 2020

However, when considering the data obtained (2018-2020), owing to the kindness of the Lloyd's Register specialists, a special problem may be detected. In particular, if a period of three years is observed (Fig. 2), it may be noted that the separators do not operate with sufficient efficiency.

In order to provide for reliable results and conclusions, over twelve thousand samples were analysed. If we take into consideration that, according to the ISO standard 8217: 2017, the maximum allowed concentration of cat fines (Al + Si) is 60ppm, it means that the separators must have an efficiency of not less than 80%. This way, they will be able to purify the fuel from 60 ppm to 12ppm, which would be in line with the recommendations of marine engine manufacturers. However, Fig.2 shows that, for each analysed year, the majority of separators had the efficiency below 80% (from 67% of samples for 2020 to as many as 80% of samples in 2019). Moreover, an ultimately alarming fact is that 45% - 49% of all the analysed samples had a very low efficiency in the elimination of these abrasive impurities (from 0% - 60%)!

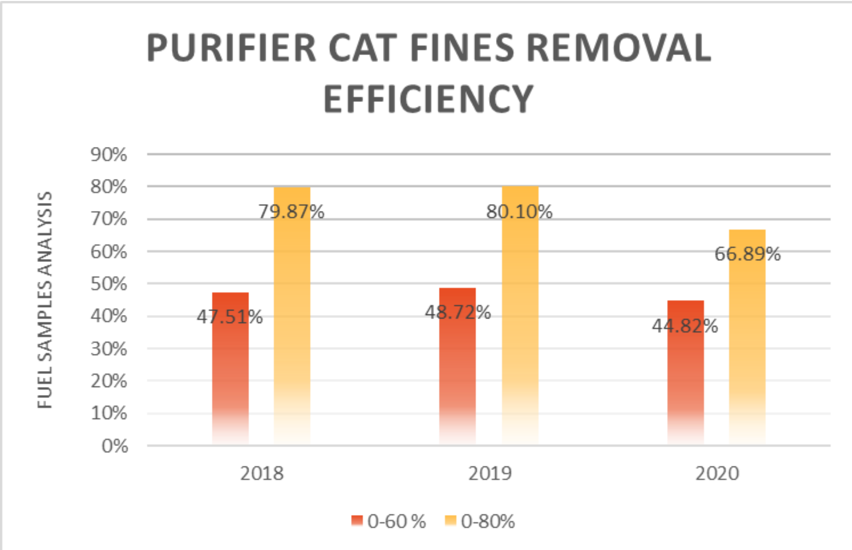

Figure 2 – Purifier efficiency in removal catalytic fines from fuel oil on ships (2018-2020)

MODEL DEVELOPMENT

The findings stated above made us think about developing a reliable model and the possibility of monitoring the quality/efficiency of the fuel oil treatment system. In the considered model, the size of the storage tank (bunker tk.) is 446 t, with the settling and service tanks having the capacity of 36 t, whereas the transfer pump capacity is 20 t/h. The daily fuel consumption of the main engine at 100% load is 45 t/d maximum continuous rating (MCR), → which can be run for an hour.

As for the developed model, normal continuous rating (NCR) will be used. The normal continuous rating for this model is at 80% MCR and the consumption under the given conditions is 36 t/d for the engine of 11,800kW. The fuel consumption on generators certainly varies due to the ship's electricity consumption, as well as the policy of the company on whether and where to use another type of fuel, that is, marine diesel oil (MDO).

This model will analyse specific cases (maximum consumption) that may be expected on a tanker ship in the following scenarios:

- When the ship is sailing at maximum speed and when she needs the minimum number of generators for normal operation (the most common case during voyage, unless the company opts for economical speed or super slow steaming (SSS)). In this case we will include the analyses of the situation when the ship is using scrubber (increased fuel consumption due to additional equipment in use);
- When the ship is in the port of discharge, that is, when the maximum fuel consumption is at the boiler and when due to the specific situation at least two diesel generators must be at work (note that this situation occurs only when cargo is being discharged, which is not so frequently). It should also be taken into account that today's

discharging operation on product tankers takes about 16 hours.

- When the ship is in navigation and when cargo requires heating, the fuel consumption on the main engine will be at the maximum, plus higher fuel consumption on the boiler and increased fuel consumption on diesel generators (this is a common situation on product tankers, depending on the fuel type).

In the model described, the problem of total fuel consumption will be specifically considered in these three extreme scenarios in which the most common case is Scenario 1. Due to the environmental considerations, increased fuel consumption will be accounted for because of the use of scrubber for exhaust gases.

Depending on the maximum fuel consumption, the load on the fuel purification system will vary. Standard fuel purification systems include filters and the most powerful element such as centrifugal fuel separator. There are many other elements that can assist in the separation of the fuel from impurities (Vukičević, Račić, & Vukašinović, 2019) but not as powerfully and effectively as the separator itself. In addition to these elements, and focusing the importance of the separator's efficiency, the company Alfa Laval proposed a way to improve the efficiency of removing catalytic impurities. According to (Alfa Laval., 2024), it is possible to increase the efficiency of purifier by 30% and additionally protect the main engine from catalytic damage by installing the latest generation Alfa Laval separator disc stack. This is an upgraded kit which may be installed by a competent Service Engineer. However, manufacturers and shipowners are generally not in favour of additional investments.

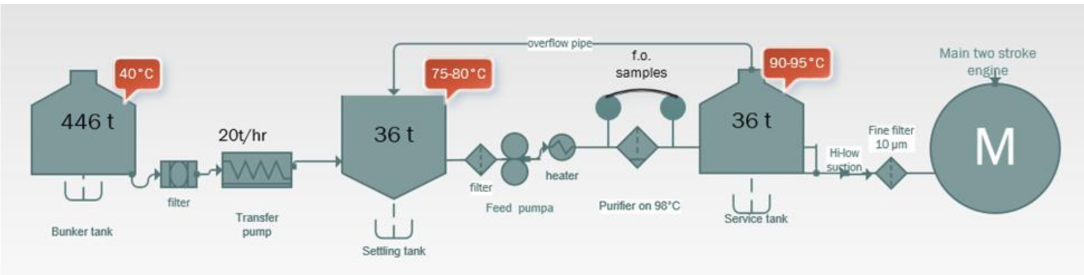

Figure 3 – Bunkering, transfer and fuel oil purification system on the model ship.

Also, by proper settling of fuel in the tanks and regular drainage, a certain amount of impurities and water may be eliminated. The maximum capacity of the analysed fuel separator in the descriptive model was 3,200 l/h. To make the model as realistic as possible, an hour a day was eliminated from calculation, which refers to the time lost during the process of sludge discharge, rinsing and restarting of the separation process. In such a case, at the maximum purifier operation, the amount of purified fuel would be:

$$3.200\ (l/h) x\ 23(h) = 73.600\ l \quad (1)$$

As may be seen, the daily fuel separation would be 73.6 m^3, while the maximum daily consumption of the main engine would be only 36 m^3. This case proves that it is unnecessary for the separator to work with 100% load, even at the maximum consumption of the main engine.

As already mentioned, the main fuel consumers on board are the main engine, generators and boilers. Therefore, it is necessary to present their consumption in the scenarios stated above (Table 1).

Table 1 – Daily fuel consumption on tanker ship

SCENARIO	DAILY CONSUMPTION ON TANKER SHIP WITH THE ENGINE OF 11.800KW				
	Main engine (M/E)	Diesel generators (D/G)	Auxiliary boiler (Aux.Blr.)	Total cons.	Load on purifier
Scen. 1 (max navigation speed)	**36 t**	3.2 t or **4.2 t with scrubber**	**0.1t** *economizer running*	**40.3 t**	**60%**
Scen. 2 (discharging cargo)	**0 t**	**5 t**	**45 t**	**50 t**	**70%**
Scen. 3 (max. speed + cargo heating)	**36 t**	**5 t**	**20 t**	**61 t**	**85%**

As may be seen in Table 1, in Scenario 1 the fuel consumption on the generators increased by 1t if a scrubber is in use, whereas the boiler operation is not required at this speed because the economizer produces sufficient quantity of steam for daily consumption. In this case, we will add only 0.1 t of its consumption for the entire day.

The model does not consider specific navigation circumstances, such as for example storm, with a great influence of wind or sea current, the influence of ballast or the "cleanliness" of the ship's keel.

In addition, engine performance is also influenced by factors such as:

- weather conditions in which the engine operates,
- resistance to air intake and back pressure of exhaust gases,
- temperature regime of engine cooling and lubrication, as well as quality of water and oil,
- gas distribution phases and gas exchange conditions,
- preload pressure,
- fuel injection pressure and fuel injection,
- evenness of fuel supply per cylinder,
- technical condition of the cylinder-piston group,
- type/quality of fuel in use.

When comparing the maximum amount of separated fuel of 73.6 t to the scenarios from Table 1, a difference may be noticed in relation to the fuel consumed. Scenarios 2 and 3 are not as common as Scenario 1 and in these cases it would be expected to increase the amount of fuel to be purified, while in Scenario 1 it may be seen that it is sufficient for the separator to operate at 60% load.

ADJUSTING THE AMOUNT OF FUEL REQURED FOR PURIFIER

In practice, it has been shown that a significant number of engineering officers do not monitor the operation of the separator, but once set, it stays that way for a long period. The problem is that they are often guided by the idea that when a larger amount of fuel is being purified, for example, at low consumption rate, it will be additionally purified during the overflow from the service tank to the settling tank. An additional problem is the lack of confidence or knowledge as they are aware of the specifics and complexity of the device. A large number of officers avoid putting another purifier in operation despite the poor performance of the fuel in use. In addition, there are hardly any fine adjustments of the purifier load. Once set, the separator is left to work that way, usually throughout the engineer(s) contract or even longer.

The complexity of the purifier device and the fact that it is usually maintained by the most junior Engineer (with the least experience) make proper handling disputable. Although the Chief Engineer has the overall responsibility for the correct operation of all the machinery, it is a rare case for them to address the complex problems of separators with additional suggestions and explanations. This would be an opportunity for junior officers to think differently and pay more attention to the operation of the purifier.

The most important parameter in setting the operation of the separator is certainly the amount of fuel that is allowed to be admitted to the separator (feed rate), as well as the fuel temperature. There are numerous cases explaining that separators with a smaller amount of fuel in their bowl are better in purifying fine impurities than when it is overfilled. It is these tiny catalytic impurities that cause problems in the engine itself. It is very important to adjust the flow and the amount the purifier needs to purify to match the total ship consumption, plus an addition of 10%. In thus it is ensured that there is always more clean fuel than that being consumed, so even if a malfunction occurs, there will be enough time to respond or start another separator.

However, the ship's crew, as said, generally leaves the same flow rate without paying attention to the fuel consumption.

PURIFIER EFFICIENCY ON THE TESTING MODEL

The efficiency of the purifier was tested on a tanker ship with a MAN B&W 6G60ME-C9 engine. The tested fuel marked RMG380 was bunkered in the port of Singapore and the analysis was performed in Viswa lab. In Table 2, a high amount of Al + Si of 57ppm may be noted.

Table 2 – Bunker fuel oil analysis results.

Bunker Port & Date:			SINGAPORE-SINGAPORE; 15-May-2021
Sample Grade:			IFO 380 - RMG 380
Bunker Quantity:			749.002 MT
Bunker Density @15°C:			988.0 kg/m^3
Bunker Viscosity @50°C:			313.6 cSt
Sulphur Content:			3.01 %
Water Content:			0.20 %
Source of the sample:			MANIFOLD
Sampling Method:			DRIP
SPECIFIED PARAMETERS FOR IFO 380 - RMG 380 & TEST RESULTS:			
Parameters	Units	Test Results	Specification Limits
Density @ 15°C	kg/m^3	985.3	(991.0 Max.)
viscosity @50°C	cSt	293.0	(380.0 Max.)
Sulphur	% (mass)	2.92	(3.50 Max.)
Water	% (vol)	0.25	(0.50 Max.)
Vanadium	ppm	176	(350 Max.)
Al + Si	ppm	57	(60 Max.)

According to some previous research from the "Cat Guar" database (MAN Diesel & Turbo, 2017) the importance of reducing the flow on the fuel separator in favour of better efficiency. The same paper points to the importance of the fuel temperature adjustments for improving the separation process. However, under the given conditions and according to the manufacturer's recommendation, it was not possible to test this.

Fig.4 explains the efficiency of the separator and its dependence on the flow through the purifier, as well as the influence of the inlet temperature of impure fuel. The purifier that works at low fuel flow, that is, at 25% flow, has as much as 90% efficiency. The results show that when the fuel temperature increases and the flow through the purifier is reduced, the fuel purifying efficiency is also increased, providing for better removal of catalytic impurities.

It should be noted here that most purifier manufacturers do not recommend purifier running at above 100°C due to water boiling.

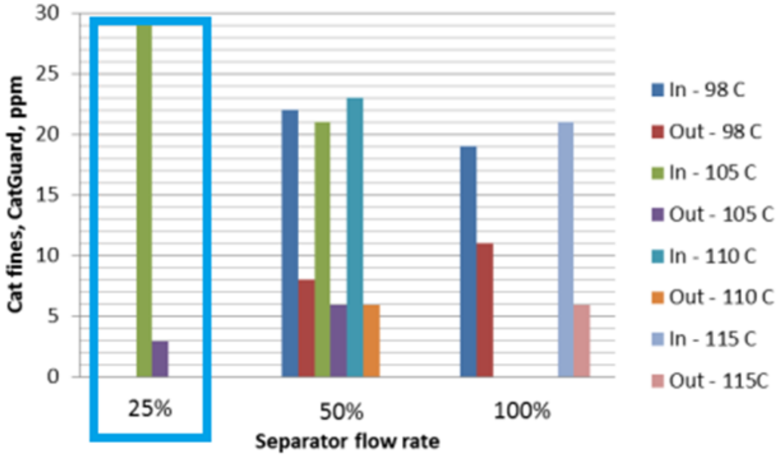

Figure 4 – Purifier efficiency in removing catalytic fines by regulating flow rate.

ADJUSTING FUEL FLOW ON PURIFIER BY USING A CALIBRATED METAL ORIFICE

Today, most modern purifiers have the ability to adjust the flow of impure fuel through them, as well as operating limits and numerous alarms that are responsible for their proper operation. There are usually two separators installed, (with the exception of for example, large container or passenger ships, where this number is usually higher). Depending on the fuel feed pump and its capacity, the amount of separated fuel will vary. On the other hand, the capacity of the feed pumps is most often associated with the capacity of the purifier, whereas it should be much higher than the daily fuel consumption on board.

In regular circumstances the operation of a single separator is considered sufficient (as it can serve the daily need for fuel). If we consider Scenario 1 from Table 1, it may be seen that in that case it suffices for the purifier to work with 60% flow. In other specific and much rarer cases, the load on the separator increases to 85%. In all the other cases (when the ship navigates at a lower speed, during manoeuvring or at anchor), this percentage drops drastically, and adjustments are necessary. Therefore, Fig. 5 shows the purifier auto-control model, developed through the Matlab program and the Simulink visual tool package.

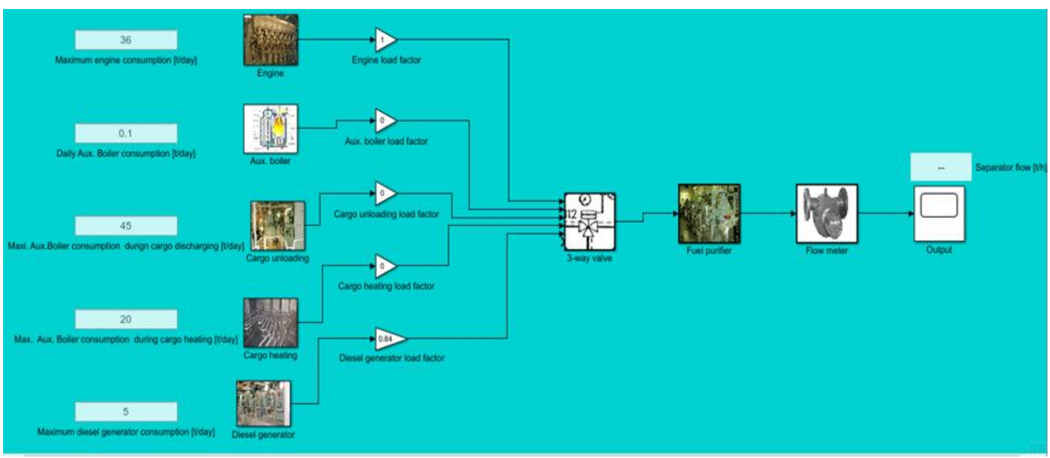

Figure 5 – Purifier efficiency in removing catalytic fines with flow rate regulation.

Fuel consumption is divided into five different categories: main engine consumption, daily regular boiler consumption, boiler consumption during cargo discharge, boiler consumption during cargo heating and diesel generator consumption. The input parameters in the simulation are the maximum daily fuel consumption for all the five categories respectively. By adjusting the load for each of the individual categories, a signal is sent showing the percentage to which the individual elements are loaded, that is, the percentage of the maximum possible fuel consumption for each of the categories. Total fuel consumption at a given moment is calculated according to:

$$\dot{Q}_{tot} = \sum_{i=1}^{5} \dot{Q}_{max,i} \cdot \eta_i \qquad (2)$$

where:

$\dot{Q}_{tot}$ [t/day] is the total fuel consumption at a given moment,

$\dot{Q}_{max,i}$ [t/day] is the maximum fuel consumption for each of the categories,

η_i [%] is the percentage of maximum possible fuel consumption for each of the categories.

Based on the current fuel consumption, a signal reaches the three-way valve and regulates the opening of the valve towards the fuel separator to the required percentage. The required percentage of valve openness is the function of the received signal and is determined through polynomial interpolation made based on the specific flow values applicable to the valve in use, maximum flow, minimum flow, flow at some specific points, etc., according to the following equation:

$$P = f\left(\dot{Q}_{tot}\right) = p_1 \dot{Q}_{tot} + p_2 \qquad (3)$$

where:

P [%] is the percentage of valve opening towards the fuel separator,

p1, p2 are the polynomial coefficients calculated based on specific flow values for the valve being used.

After passing through the valve, the fuel passes through the fuel separator and flow meter where its flow rate is read.

On modern types of separators, the process of separation and discharge of accumulated sediment and water is performed automatically. It is necessary to periodically check the operation of the purifier, along with control and alarm notification systems. Some of the alarms that may be sounded during this process are low/high fuel pressure alarm, high/low fuel temperature alarm, high vibration alarm, freshwater shortage (displacement and flushing water), water drain error alarm, etc.

It is known that in case the purifier is not able to release sludge and water, the control unit repeats the procedure, the fuel is returned to the tank or recirculated to the system via a 3-way valve (Fig. 5).

The flow of impure fuel through the separator is often regulated by controlling the "back pressure" valve, which regulates the back pressure, as may be seen on Fig. 6. The process of heavy fuel oil separation on two different types of tanker ships was simulated on engine room simulators. This simulator is equipped with main engines marked MAN B&W 6S50MC-C and MAN B&W 6S60MC-C (which correspond in size and type to the ship's system and the ship in operation with which the comparison was made). The simulation was done by adjusting the valve to the maximum value allowed on the simulator.

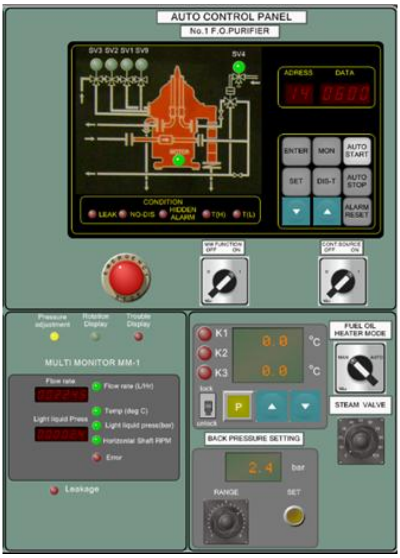

Figure 6 – Flow regulation on purifier no.1 via Auto Control Panel

It was possible to adjust the flow attenuation to up to 50%, that is, up to 35.4% of the purifier capacity. Lower values could not be simulated, and separation efficiency data are given in the table below.

From Table 3, it may be seen that on the 60MC model it was not possible to reduce the flow to below 50%. Due to the impossibility to further reduce the amount of flow, any further elimination of fine impurities was not possible either. In real-life situations, however, it is possible to achieve this by using metal calibrated orifices (shown in Fig.7). In this case, it should be noted that when reducing the flow on the separator, certain amount of pressure was created on the heaters because the fuel could not pass through the valve with a spring (Fig. 7).

Table 3 – Fuel oil purifier efficiency on engine simulators.

	SIMULATOR MODEL	
	MAN B&W 6S50 MC	MAN B&W 6S60 MC
Purifier load	Flow (l/h) – purifier efficiency (%)	
100%	2460 l/h - 61%	2961 l/h - 61.5%
75%	1875 l/h - 71%	2291 l/h - 68.3%
50%	1255 l/h - 79%	1523 l/h - 75.5%
35.4%	883 l/h - 85%	n/a

Figure 7 – Valve with a spring and calibrated orifice for regulating the fuel flow.

By inserting a calibrated orifice, it was possible to influence the spring, so the fuel could normally pass back into the fuel tank. This way, it was possible to achieve the desired flow rate. The capacity of the feed pump was, as in the simulation, 3,200 l/h, and in the way described above, the flow was reduced to as much as 800 l/h, that is to 25% of the flow (Fig. 8).

To confirm the justification for these procedures, a sample of purified fuel was analysed at the Viswa lab laboratory. The efficiency of fuel separation when it comes to catalytic impurities (Al + Si) at the minimum flow was as high as 81% and above average (Fig. 9). In addition to the efficient elimination of impurities, a reduction in the finest impurities, specifically those of 4.6 and 14 microns, is also notable.

Figure 8 – Display of adjustable, maximally reduced flow through the fuel separator using calibrated orifice

ANALYSIS OF WATER, SEDIMENT AND METALS

	REFERENCE PARAMETERS			PURIFIER PERFORMANCE PARAMETERS						
LOCATION	Den	Vis	Sul	H2O	TSE	Al+Si	NA	FE	CA	PEFN
DRIP SAMPLE	985.3	293.00	2.92	0.25	0.03	57	21	16	8	35*
BEFORE PURIFIER # 1	985.2	319.50	2.94	0.15	0.02	43	19	13	8	41
AFTER PURIFIER # 1	985.3	330.70	2.92	0.15	0.01	8	12	7	4	54
IMPROVEMENT IN PURIFIER %				0	50	81	37	46	50	
OVERALL PURIFIER EFFICIENCY				Above Average						

PARTICLE COUNT ANALYSIS

LOCATION	> 4µ	6µ	14µ
BEFORE PURIFIER # 1	19	17	15
AFTER PURIFIER # 1	17	15	13

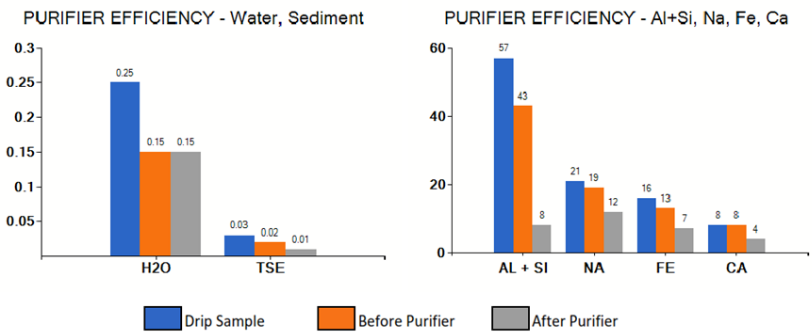

Figure 9 – Efficient elimination of catalytic impurities by reducing fuel flow

CONCLUSION

Catalytic impurities in the fuel can create huge problems and high costs on board in a very short period of time. Their impact will greatly contribute to the wear of vital parts on the main engine. In order to reduce this impact, it is necessary to influence the ship's fuel purification system. In addition, a regular analysis of the purifier efficiency should be done in order to provide a timely response for avoiding severe and dangerous wear. The shipowners aim for the most cost-efficient way to provide them with a safe system and reliable engine operation. In this paper, we wanted to show that there is still a large number of separators that operate at an unsatisfactory level of efficiency, which is one of the prerequisites for good quality fuel separation. It is known that reducing the flow on the separator increases its separation efficiency in regard to abrasive impurities. Nevertheless, in reality this flow is not adequately regulated, or it cannot be reduced below a certain flow rate. The paper also shows that the use of calibrated orifices can lead to an additional reduction in fuel flow to as much as 25% (when there is no high fuel consumption). This would result in a significantly enhanced separation of catalytic impurities from the fuel. Considering that the paper takes into account the extreme cases of fuel consumption on a tanker ship, in all other cases the load on the separators is expected to be significantly lower.

At lower loads, that is, with low fuel consumption, the purifier efficiency may be influenced by adding an orifice, while in other cases it is necessary to do fine flow regulation. This is feasible by automatic regulation of the flow through the purifier and optimization of the system itself.

DECLARATIONS OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest to declare in relation to the research presented in this paper.

LITERATURE

Alfa Laval (2024). Alfa Laval Separation Efficiency Upgrade, Certified Flow Rate (CFR) and increased engine protection, Retrieved March 4, 2024, from https://www.alfalaval.com/globalassets/documents/service/marine-service/seu-pd-leaflet.pdf

Innospec tehnical bulletin, Marine fuel specialties. (2020). Customer Technical Service VLSFO REPORT - Q1 2020, April 2020. Retrieved March 1, 2024, from https://www.octamar.info/wpcontent/themes/innospec/documents/IOSP%20Marine%20technical%20bulletin%20April%20issue%201.pdf.

MAN Diesel & Turbo (2017). *Cat Fines Impact on engine wear and how to reduce the wear*. Man Diesel & Turbo, 29-11-2017/DOJA.

Vukičević, M., Račić, N., & Ivošević, Š. (2019). Piston ring material in a two-stroke engine which sustains wear due to catalyst fines. *Brodogradnja: An International Journal of Naval Architecture and Ocean Engineering for Research and Development*, *70*(2), 155-169. http://dx.doi.org/10.21278/brod70208.

Vukičević, M., Račić, N., & Vukašinović, D. (2019) Heavy fuel treatment from the aspect of harmful action of cat fines. *Collection of papers of the Maritime Faculty Kotor*, *35*(22), 117-139.