AN OPTIMIZATION OF MARINE DIESEL ENGINE OPERATION PARAMETERS WHEN USING A MIXED FUEL (DO AND PALM OIL) AS ALTERNATINE FUEL

Prof. DSc. Dang Van Uy*, Prof. Dr. Nguyen Dai An† and MSc. Nguyen Duc Hanh†

* † Vietnam Maritime University
No. 484 Lach Tray street, Hai Phong city, Viet Nam
e-mail: vanuydang@gmail.com, web page: http://www.vimaru.edu.vn

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Abstract. The purpose of this article is to introduce a optimization method to reset technical parameters of fuel suplly system in order to allow marine diesel engines to use mixed fuels (vegetable oils &DO) to match required exhaust gas emissions and engines' performance without any problems.

1 INTRODUCTION

At present time, a tendency of using alternative fuels such as mixed fuels (vegetable oils and DO) for diesel engines in general and for marine diesel engines particularly is very common worldwide. Because, the mixed fuels have potential ability to reduce emissions in exhaust gas of diesel engines and be dependent from the fosil fuel in the future. The results of many researchs showed that diesel engines using mixed fuels can decrease a content of not only NO_x and also SO_x in exhaust gas.

However, when the mixed fuel (DO & Vegetable oil) used to subtitute the conventional fuel for diesel engines may influence negatively on the fuel combustion inside cylinders, then consequently on their performance. Firstly, the different physical features and chemical structure of mixed fuels can make worse fuel combustion in marine diesel engines. Secondly, the different properties of mixed fuels can influence on the engines' injection timing and consequently on their exhaust gas emissions and fuel consumption. So, in order to use mixed fuels without any problem, an adjustment (re-setting) of fuel supply system of marine diesel engines must be taken into consideration. Therefore in this paper, authors will introduce a method to optimize technical parameters of fuel supply system of marine diesel engines using mixed fuels in order to match required exhaust gas emission limitations and performance.

2 THEORETICAL METHODOLOGY APPLIED FOR INVESTIGATION

The research is conducted into stages as follows: Firstly, there have to evaluate influences of a mixed fuel on operation parameters of a diesel engine such as fuel combustion inside cylinders, exhaust emissions and performance in comparison with that of the same diesel engine when using conventional fuel set by the engine maker previously; Then, results obtained by calculation or simulation should be analyzed carefully in order to predict main factors and tendency that impact on operation parameters of a diesel engine; Finally, on a base of analysis results, there can use suitable optimization tool to do new settings for the engine to meet the required goals.

As well known, the changes of mixed fuels' properties associated with differences in chemical structure in comparison with conventional fuel will impact on the engine injection timing. The properties that will make main affects on the fuel injection timing are the speed of sound, the isentropic bulk modulus and the fuel viscosity. Furthermore, the ignition delay also is significant factor that can make changes of characteristic of combustion pressure inside diesel engine cylinders and the properties of fuel also are reasons to make changes of the ignition delay of diesel engines. Since the ignition characteristics of a fuel affect the ignition delay, this property of fuel is very important in determining diesel engine operating characteristics such as a fuel conversion efficiency, misfire, smoke emissions and so on.

In order to implement the investigation, mathematical formulas and simulation models are applied as following [1]:

- The impact of sound speed on fuel injection timing can be estimated for fuel supplied system by using the speed of sounds of diesel oil and a mixed fuel by following formula:

$$K = c^2 \rho \tag{1}$$

Where K is the isentropic bulk modulus [Pa], c is the speed of sound of a liquid [m/s] and ρ is density of a liquid [kg/m^3].

- The impact of the isentropic bulk modulus can be calculated by a well-known model for fuel compression as following:

$$\varphi_{inj} = \frac{(p_{inj} - p_0)V_f}{K v_\varphi A_p} \tag{2}$$

Where: φ_{inj}- a crankshaft rotation required to reach a nozzle open pressure [^{0}CA]; p_{inj}- nozzle open pressure [Pa]; p_0- initial system pressure [Pa]; V_f-volume of compressed fuel [m^3]; K- isentropic bulk modulus [Pa]; v_φ- speed of plunger [m/s]; A_p- area of plunger [m^2].

- Correlation for ignition delay in diesel engines

There are many correlations that have been developed for predicting ignition delay, but the formula proposed by Hardenberg and Hase is choosen and expresed as [5]

$$\tau_{id}(CA) = \left(0.36 + 22\overline{S}_p\right)\exp\left[E_A\left(\frac{1}{\tilde{R}T} - \frac{1}{17,190}\right)\left(\frac{21.2}{p - 12.4}\right)^{0.63}\right] \tag{3}$$

Where: $\overline{S_p}$ - the mean piston speed [m/s]; $\tilde{R}$ - the universal gas constant (8.3143J/mol.K); E_A - the apparent activation energy [J/mole].

- Fuel spray atomization and droplet size

To express fuel droplet size is very complicated, so the concept of the Sauter mean diameter (SMD) is applied and an empirical expression for the Sauter mean diameter DSM for diesel fuel properties proposed by Hiroyasu and Kadota is [5]

$$D_{SM} = A(\Delta p)^{-0.135} \rho_a g_f^{0.131} \tag{4}$$

Where Δp- mean pressure drop across a nozzle [MPa]; ρ_a- air density [kg/m^3]; g_f- amount of fuel delivered per cycle per cylinder [mm^3/cycle]; A- constant which equals 23.9 for hole nozzle, 25.1 for pintle nozzles.

- Optimization method

A meaning of optimization of working parameters of diesel engines is concerning with minimizing exhaust gas emissions, specific fuel consumption and good performance of diesel engines. The response surface methodology will be applied and mathematical model can be expressed [3]:

$$y = f(x_1, x_2, x_3 \ldots\ldots x_n) \pm \varepsilon \tag{5}$$

Where y is dependent variable, f is response function, x_i are dependent variables and ε is the fitting error. The goal of response surface methodology is to rapidly and efficiently reach the vicinity of the optimum. Therefore, the first order-model will be appropriate to solve the requested problems. To use response surface methodology as an optimization technique, a mathematical model of goal must be defined in form of an objective function. In this case, to optimize exhaust gas emissions and fuel consumption of a marine diesel engine using a mixed fuel, an objective function will be applied as follow [4]:

$$f(x) = Merit = \frac{1000}{\left(\frac{NO_x}{NO_{x,g}}\right)^2 + \left(\frac{g_e}{g_{e,g}}\right)} \tag{6}$$

NO_x – measured emission level; g_e- fuel consumption; $NO_{x,g}$- goal emission level; $g_{e,g}$- goal fuel consumption.

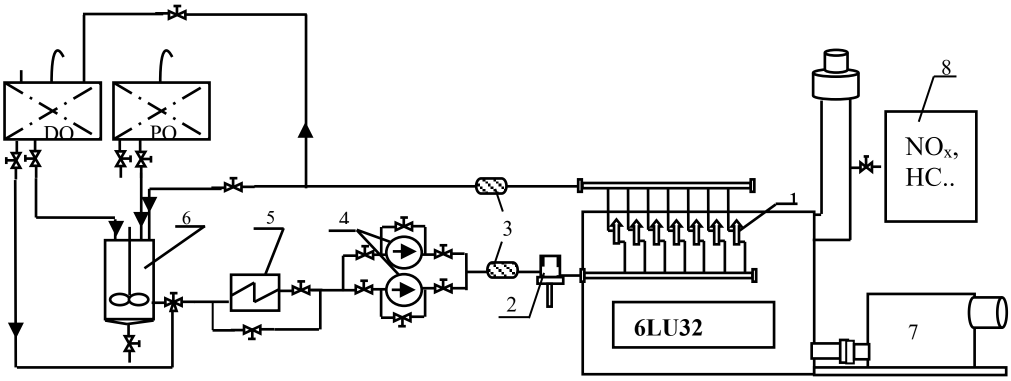
3 INVESTIGATION RESULTS

An experiment, then has been curried out on Hansin marine diesel engine 6LU32 equipped at Lab of Faculty of Marine Engineering (Vietnam Maritime University). The marine diesel engine with an output of 900kW at speed of 340rpm is driving a hydraulic brake. The Lab also is equipped with modern measuring instruments supplied by well-known company AVL (Austria). The mixed fuel that is selected for the investigation is a fuel produced by mixing diesel oil (DO) with pure palm oil with different ratio from 5% to 30%.

3.1 Arrangement of testing equipment

The equipment used to carry out experiment and their arrangement are showed in Fig.1.

In the research, an alternative fuel is a mixed fuel (or blended fuel) between diesel oil (DO) and pure palm oil in different volume ratio [%] and chemio-physical properties are showed in Table 1[6].



1 - High pressure pump; 2 –Final filter ; 3 – Flowmeter; 4 - Transferring pump mixer;
5 -Heater; 6 - Fuel continuous; 7 –Hydraulic brake; 8 – Gas analyzer (emissions)

Figure 1: Arrangement of testing equipment

Table 1: Fuel features of blended palm oil

No	Fuel characteristic	Blended fuels and DO				
		DO	PO10	PO20	PO30	PO100
1	Density at 15°C, [kg/dm^3]	0.8464	0.8538	0.8599	0.8668	0.9225
2	Viscosity at 40°C, [cSt]	2.6	3.42	5.31	6.45	40.24
3	Cetane number	42.89	50.13	50.91	52.11	52.92
4	LHValue, [MJ/kg]	44.978	43.650	42.960	42.29	40.11

3.2 Evaluation of fuel properties impact on fuel supply system

The impact of fuel properties on injection timing and fuel combustion of diesel engines is very different and complicated. Therefore, first stage should be taken into consideration before implementing an optimiaztion of the engine operation parameters is theoretical evaluation of fuel properties influence on the fuel supply system. Results of such evaluation will support so much the optimization process by decreasing a number of the optimization stages and the control factors.

Table 2: Results of fuel properties impact

Fuel properties	Kind of fuel		Difference
	DO	Mixed fuel	[^{0}CA]
Speed of sound	1.808^{0}CA;(8.876.10^{-4}s)	1.759^{0}CA;(8.634.10^{-4}s)	0.05
Bulk modulus	3.63^{0}CA	3.33^{0}CA	0.3
Size of droplet	31.17μm	31.31μm	0.14μm (0,5%)

Then, the impact of the sound speed and of the bulk modulus of the mixed fuel estimated by using formula /1/ and /2/ is expressed in Table 3. For the calculation, the speed of sound should be taken in working conditions with temperature at 40^{0}C and pressure at 18MPa and c_1=1430.68m/s for diesel oil No2, c_2= 1470.83 for mixed fuel (the speed of sound for mixed fuel is an average value that is asumed on a base of speed of mixed fuel with different ratio of palm oil from 5% to 25%). The length of high pressure tube from high pressure pump to nozzle is equal to 1.270m and revolution is 340rpm (marine diesel engine 6LU32). The analysis of fuel droplet size has also been realized and resuts of the analysis is expressed in Table 2.

Regarding to fuel ignition delay, on a base of formula /3/, the calculation results for different ratio of palm oil in the mixed fuels are showed in table 3 [6,7].

Table 3: Calculated ignition delay of mixed fuels

Ignition delay in $[^0CA]$	**Blended fuels**					
	DO	**PO5**	**PO10**	**PO15**	**PO20**	**PO100**
	2,1978	2,2049	2,2127	2,2158	2,2181	2,3003
Increasing $[^0CA]$ và [%] in comparison with DO	- -	0,007 0,30	0,0140 0,60	0,018 0,80	0,020 0,910	0,101 4,595

So, on a base of the results of analytical analysis, there can asume that: The sound speed and isentropic bulk modulus of the mixed fuel make the start of fuel injection (SOI) earlier 0.05^0CA and 0.3^0CA respectively in comparison with diesel oil; otherwise, the activation energy (Cetane numer) of the mixed fuel also increases fuel ignition delay by everage 0.018^0CA; The droplet size of the mixed fuel is increased not so much, only by 0,5%, but it can impact on fuel combustion process rather significantly [5]; Except the mentioned factors, there are many other factors can impact on the injection timing and fuel ignition delay, so there can take injection timing advance of approximately 1^0CA for further investigation.

Actually, the investigation results are only orientating and in practice, the impact of the mixed fuel properties is very complex. However, the results can open an right way for further research of optimization of the diesel engine operation parameters in next sections.

3.3 Optimization of operation parameters of diesel engine

The experiment was carried out on the marine diesel engine 6LU32 after getting the assessment results by calculation of the mixed fuel properties influence on injection timing and fuel droplet size distribution. Before implementing the experiment, a domain of investigation has been set as follows: Experiment should be carried out only on the engine load range around 80% of the nominal load; Exhaust gas emission should be focused on NO_x that is strictly requied by IMO (Annex VI, MARPOL73/78).

Table 4: Factor variables

Variables	**Symbols**	**Levels**		
		Lower (-1)	Center point (0)	Upper (1)
Start of injection [^{0}CA BTDC]	A	10.5	12	14.5
Injection pressure [MPa]	B	17	18	19
Ratio of Palm oil [%]	C	10	15	20

The control factors are start of injection (SOI), injection pressure (IP) and ratio of palm oil in the mixed fuel (PO). The start of injection was choosen as SOI value after correction, the injection pressure was choosen as original value designed by the engine manufacture (18MPa) and ratio of PO are 10%, 20% and 30% and all the control factors are considered as center points. So, the control factors can be seen in the Table 4.

Fllowing up with the procedure of the development of experiment method using the RSM, the experiment was impemented on the center points and in accordance with the experiment matrix as presented in Table 5 and all the factor variables have been coded.

Table 5: Experiment design matrix

No	X_0	X_1	X_2	X_3	Y_1	Y_2
1	1	1	1	1	223.5	15.3
2	1	1	1	-1	219	15.6
3	1	1	-1	1	222.5	15.2
4	1	1	-1	-1	221.4	15.7
5	1	-1	1	1	221.5	16.1
6	1	-1	1	-1	222	16.5
7	1	-1	-1	1	224.2	16.4
8	1	-1	-1	-1	222.6	16.8
9	0	0	0	0	221g/kWh	16.1g/kWh

On a base of table 5, the regression models for the fuel consumption estimation (Y_1) and NO_x emission (Y_2) are established as follows:

$$Y_1 = 222.08 - 0.487X_1 + 0.587X_2 + 0.712X_3 \tag{8}$$

$$Y_2 = 15.95 – 0.5X_1 – 0.075X_2 – 0.2X_3 \tag{9}$$

The above regression models are very usefull to analyse which factor variable is most significant influence on the fuel consumption and NO_x emission of the diesel engine. To do so, ANOVA is used to analyse and give results that (Fig.2):

- The factor PO% most influences on the specific fuel consumtion ge, then the injection pressure and the start of injection factor (SOI);
- The factor SOI has most important role to change the NOx emission, then the injection pressure and the factor PO% play least role.

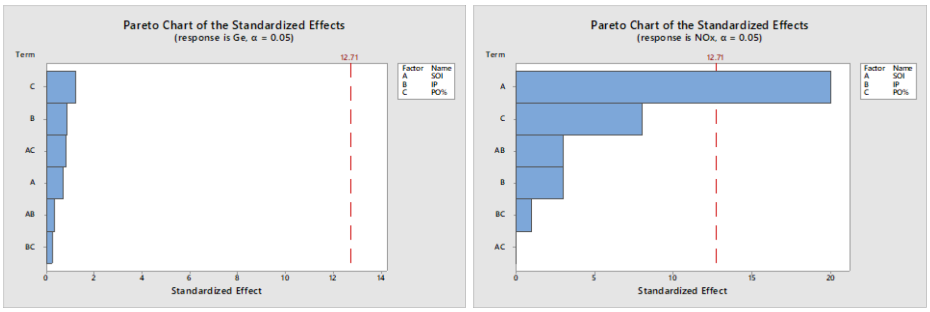


Figure 2: Pareto chart standardized effect on g_e, NO_x

So there can see that the ratio of palm oil in the mixed fuel has bigest impact on the fuel consumption, then the injection pressure. In case of NO_x emission, the start of injection is main factor, then the ration of palm oil.

To check the validity of the fitted models, the residual analysis is also conducted by using

Minitab software 18 and the results are presented at Fig. 3.

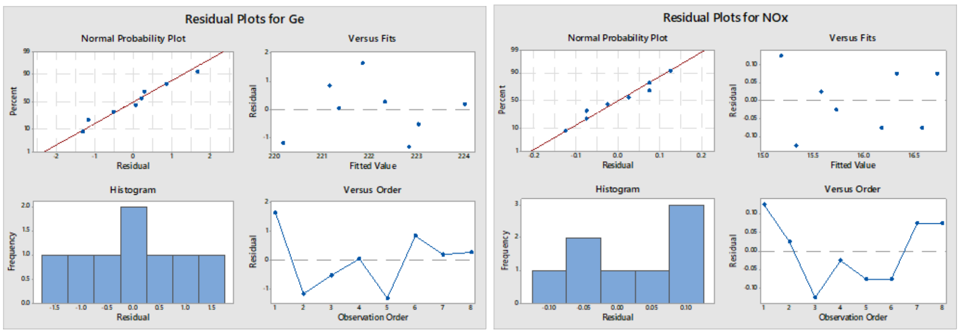


Figure 3: Foure-in-One residul plots for g_e and NO_x

Based on these analyses, then the factor variable can be adjusted in acoordance with the rule of the fractional factorials and the steepest descent method of optimization. Because, the use of fractional factorials is a most effective technique to minimize the number of observations and still achieves desired objective. Selection of a moving step for the control factors: based on the basic control factors and the regression equetions, a moving step δ_i can be calculated and the results are showed in table 6.

Table 6: Control factors for fractional factorial experiment

Levels	**Control factors**		
	X_1 SOI [^{0}CA BTDC]	**X_2** IP [MPa]	**X_3** Ratio of PO [%]
Center point	12	18	15
Changing step [Δ_j]	2.5	1	5
Coefficients	-0.48 and -0.5	0.58 & 0.075	0.712&-0.2
$b_j\Delta_j$	-1.25	0.58	3.56
Moving step	-0.877	0.407	2.5
Full number	-1.0	0.5	2.5

- Results of experiment

The experimet, then has been implemeted by using the moving steps mentioned in table 6 and the objective function (8) was used to evaluate an opimization throught the remit levels. The experiment results are presented in table 7.

Table 7: Results of optimization research

No	**X_1** SOI [^{0}CA]	**X_2** IP [MPa]	**X_3** Ra. of PO [%]	**Y_1** g_e [g/kWh]	**Y_2** NO_x [g/kWh]	**Remit**
Cen. point	12	18	15	221	16.1	427.42
2	11	18.5	17.5	220	16.0	431.24
3	10	19	20	218.5	14.8	469.86
4	9	19.5	22.5	219	14.1	**492.58**
5	8	20	25	221	14.3	483.58
6	7	20.5	30	225	15.9	429.75

The NO_x limitation required by International Maritime Organization is expressed in Chapter VI, MARPOL 73/78 that can be calculated as function of the engine revolution. So, marine diesel engine 6LU32 with the nominal operation speed of 340rpm, the NOx limitation is equal to 14.19g/kWh and then, the goal limitation emission $NO_{x.g}$ = 14.19g/kWh . Meanwhile, the goal fuel specific consumption of this engine $g_{e.g}$ = 210g/kWh.

Through the results of remit, there can confirm that the combination (SOI=9^0CA, IP=19.5MPa, Ratio=22.5%PO) has a remit with highest value. This also means that the opimization process has found the optimal control factors for diesel engine 6LU32 and SOI=9^0CA, IP=19.5Mpa, mixed fuel PO22.5 can be selected to set optimium working parameters for diesel engine 6LU32 to use the alternative fuel to subtitute the conventional fuel.

4 CONCLUSIONS

Resetting operation parameters of marine diesel engines is allways necessary for any change of using a new fuel, especially using mixed fuel (alternative fuels). The above mentioned method has been applied to reset the technical parameters of fuel supply system of marine diesel engine 6LU32 for the purpose of using the mixed fuel (pure palm oil & DO) and these gave very positive results. So, there can draw some conclusions that:

- The response surface method is good tool to optimize the working parameters of a marine diesel engine when the diesel engine is converted to use mixed fuel (alternative fuel) to replace the conventional fuel (fossil) in order to achieve the objective of environment protection and energy saving. After re-setting in accordance with newly chosen parameters (SOI, NOP, mixing ratio) by above mentioned method for fuel supply system, the marine diesel engine has been working well with proper exhaust gas emission (NO_x) and fuel consumption;
- The optimization method is simple and very practical one and it can be applied in order to re-sett technical parameters of a fuel supply system for any marine diesel engine when it will use an alternative fuel to substitute conventional one.

However, the investigation is just beginning and the investigation results are collected from one diesel engine. So, for more practical application, there needs further development of the method and applications should be carried out on existing ships.

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