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Calculation method of the specific fuel oil consumption in low-speed marine diesel engines

SUMMARY

The paper presents a calculation method of the specific fuel oil consumption in low-speed marine diesel engines,based on a multi-level regression analysis for data available from catalogues issued by the engine makers, considering the data as statistical sets.

The obtained functional relationship yields results differing by less than 5.5% from their respective catalogue values. The comparison is made for more than fifty engine types of Sulzer and MAN-Burmeister & Wain make.

In the years 1980-1990 very fast development of low-speed marine diesel engines was observed. The diesel engines of the notably diversified specific fuel oil consumption (**sfoc**) were offered on the market. A large degree of similarity may be found in construction of the offered engines. Mutual similarity of contemporary low-speed diesels concerns the following features:

- course of thermal process (two-stroke working cycle, longitudinal, valve-wards cylinder scavenging);
- supercharging system (of constant pressure, single stage, water-cooled type);
- injection system (of single or multi-point, high pressure direct injection type);
- combustion chamber cooling system (intensive water-cooling of ducted flow in opposite-to-expansion direction);
- piston crown cooling system (heat transfer by washing the internal side of the piston crown);
- lubricating system of the cylinder liner bearing surface (multi-point lubrication with application of lubricators); aa well as :
- number of cylinders and their arrangement (number of cylinders: from 4 to 12, in-line cylinder arrangement).

The similarity features characterize particularly conditions of the fuel energy conversion into the mechanical one and a way of its transmission to the engine coupling. The similarity exists for the basic parameter - stroke/bore ratio: S/D, where S - stroke of piston, D - diameter of piston, and within the variability range of the parameter : < 2; 3.82 >.

It has been assumed that the S/D ratio may serve - due to the above mentioned similarity - as an index for distinguishing a design version of the contemporary low-speed engine.

Apart from the described constructional features of the engines, a similarity in engine testing methods on the test bed is also important. Ship diesel engines are tested on the test bed in compliance with the established nominal propeller curve. Results of the tests serve as the basis for appraisal of engine performance. The **sfoc** value is of the basic significance among other external engine parameters measured on the test bed. The **sfoc** values are till now available for merchant ship designers and operators first of all in a form of individual parameters given in engine maker's catalogues.

Values of engine parameters may be determined either from relevant tables or diagrams provided there. It is also possible to determine a value of the **sfoc** allowance for the low-speed engine, working in a specified point of the layout diagram, with respect to the maximum continuous engine rating N_{MCR} or the contract continuous engine rating N_{CMCR}.

It is not easy task to make use of catalogue information about the **sfoc.** The characteristic feature of the catalogue **sfoc** values for low-speed engines is that they relate to a fuel oil of the standardized specification and reference external conditions for engine operation complying with the ISO standards.

The following parameters are set up in the standards:

- fuel oil lower calorific value : 42707 kJ/kg;
- blower inlet pressure: 1 bar;
- blower inlet temperature: 25^{0} C;
- charge air coolant temperature: 25^{0} C;
- relative air humidity: 60%.

The above presented mutual similarity features of low-speed engines and comparable methods of determination of their **sfoc** values during the bed-testing have been taken as a basis for an attempt to describing in a synthetic way the **sfoc** of the low-speed marine diesels by a mathematical expression [1,4].

It has been assumed that **sfoc** is a result of developing the brake horse power N by an engine and that it is defined by the S/D ratio and parameters related to the coordinates of the specified MCR point (n_{MCR},N_{MCR}). The published information [2] about a qualitative relationship between values of the S/D ratio and of the **sfoc** for a low-speed engine [2] has been an advantageous circumstance for this attempt.

A multi-level regression analysis was performed for data available from catalogues issued by the leading engine makers, considering the data as statistical sets.

Having applied n-times the least square method, the following functional relationship for calculating the **sfoc** values is obtained (1) :

$$b_{MEO} = \left[340.38 - 54.385(S/D) + 6.935(S/D)^2\right]\alpha^{0.0333}N^{-0.0333} - \beta(510.71\alpha - 277.81) + \\ -(1+\beta^2)(147.34 - 263.13\alpha)\ [g/kWh]$$

where:

$\alpha = N/N_{MCR}$ - brake horse power ratio;

$\beta = n/n_{MCR}$ - engine speed ratio;

S/D - stroke/bore ratio, and:

N_{MCR} - maximum continuous horse power of the engine, [kW];

n_{MCR} - engine speed at the MCR horse power, [rev/min];

N - brake horse power of the engine ($N \le N_{MCR}$), [kW].

The above defined expression is valid within the following ranges of the respective parameters:

$\alpha \in$ <0.55; 0.85 (0.9) > ;

$\beta \in$ <0.72; 1> ;

S/D $\in$ < 2; 3.82 > ;

N_{MCR} $\in$ < 1460; 45600 > [kW].

For parameter values out of these ranges the expression (1) may yield results loaded with too large errors. This expression is applicable for the two-stroke, low-speed marine diesels with in-line cylinder arrangement, constant-pressure supercharging system, and intended to burn residual fuel oils.

Having transformed the expression (1) with respect to N_{MCR} the following is obtained (2) :

$$b_{MEO} = \left[340.38 - 54.385(S/D + S/D^2)\right]N_{MCR}^{-0.0333} - \beta(510.71\alpha - 277.81) + \\ -(1+\beta^2)(147.34 - 263.13\alpha)\ [g/kWh]$$

The catalogue values of the **sfoc** and those calculated from the presented expression are shown in the Tab. 1, 2, and 3 of the Appendix. The expression may be useful for designers and operators of ships propelled by low-speed diesel engines. Ship designer, having determined a value of the brake horse power N for a given contract ship's speed v by using the Admiralty or Hansen's formula [3], is able to estimate a value of the α parameter. Then he may determine a value of the β parameter on the basis of the propeller curve. Assuming now a value of the S/D ratio, it is possible to calculate from the b_{MEO} formula a value of the **sfoc**.

Similarly, having measured: the engine torque M [kNm] and the engine speed n [rev/min] for a ship in service, it is possible to determine the brake horse power of the engine from the formula:

$$N = M\frac{\pi \times n}{30},$$

and the α and β parameter values.

Knowing the S/D ratio of the aboard installed main engine it is also possible to calculate the **sfoc** value of the engine from the b_{MEO} formula.

CONCLUSIONS

The presented relationship makes it possible to calculate the **sfoc**(b_{MEO}) values for all contemporary low-speed diesel engines used for propelling merchant ships.

The formula yields sufficiently exact results. A deviation of the calculated **sfoc**(b_{MEO}) values from their respective catalogue values (b_{KAT}) are of the order of the error estimated by engine makers for the catalogue values of their low-speed engines.

A relatively greater deviation is observed for low-speed engines with the pulsatory supercharging system.

The presented relationship is an attempt aimed at improving design procedures (especially the parametric ones) and effectiveness of operation of contemporary sea-going cargo ships.

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APPENDIX

Tab. 1. Comparison of the catalogue - b_{KAT} and calculated - b_{MEO} values of the specific fuel oil consumption at the MCR point (n_{MCR}, N_{MCR}) of the low-speed marine diesel engines

ENGINE TYPE	$\frac{S}{D}$	α	N [kW]	β	$b_{KAT.}$	b_{MEO}	$\delta = \frac{b_{KAT}-b_{MEO}}{b_{KAT}}$ [%]
					g/kWh		
4 K 90 GA	2	1	11 612	1	190,2	188,6	0,84
8 K 90 GA	2	1	23 224	1	190,2	184,2	3,15
12 K 90 GA	2	1	34 836	1	190,2	181,8	4,42
4 L 90 GA	2,42	1	11 612	1	184,8	181,3	1,89
8 L 90 GA	2,42	1	23 224	1	184,8	177,1	4,17
12 L 90 GA	2,42	1	34 834	1	184,8	174,7	5,46
4 L 90 GB	2,42	1	13 452	1	180,7	180,4	0,17
8 L 90 GB	2,42	1	26 904	1	180,7	176,2	2,49
12 L 90 GB	2,42	1	40 356	1	180,7	173,9	3,76
4 RTA 84	2,86	1	13 240	1	171,2	174,8	-2,1
8 RTA 84	2,86	1	26 480	1	171,2	170,8	0,23
12 RTA 84	2,86	1	39 720	1	171,2	1[illegible]8,5	1,58
4 K 90 MC	3,00	-1	15 200	1	171,2	172,6	-0,82
8 K 90 MC	3,00	1	30 400	1	171,2	168,6	1,52
12 K 90 MC	3,00	1	45,600	1	171,2	166,3	2,86
4 L 90 MC	3,24	1	14 840	1	171,2	170,8	0,23
8 L 90 MC	3,24	1	29 680	1	171,2	166,9	2,51
12 L 90 MC	3,24	1	44 520	1	171,2	164,6	3,85
4 L 80 GB	2,44	1	10 392	1	182,1	181,7	0,22
8 L 80 GB	2,44	1	20 784	1	182,1	177,5	2,53
12 L 80 GB	2,44	1	31 176	1	182,1	175,1	3,84
4 RTA 76	2,89	1	10 840	1	172,5	175,7	-1,85
8 RTA 76	2,89	1	21 680	1	172,5	171,6	0,52
12 RTA 76	2,89	1	32 520	1	172,5	169,3	1,85
4 K 80 MC	3,00	1	12 120	1	172,5	173,9	-0,81
8 K 80 MC	3,00	1	24 240	1	172,5	169,9	1,51
12 K 80 MC	3,00	1	36 360	1	172,5	167,6	2,84
4 L 80 MC	3,24	1	11 680	1	172,5	172,2	0,17
8 L 80 MC	3,24	1	23 360	1	172,5	168,2	2,49
12 L 90 MC	3,24	1	35 040	1	172,5	165,9	3,82
4 S 80 MC	3,82	1	13 400	1	171,2	169,1	1,23
8 S 80 MC	3,82	1	26 800	1	171,2	165,2	3,51
12 S 80 MC	3,82	1	40 200	1	171,2	163,4	4,79
6 L 67 GB	2,54	1	11 082	1	183,4	179,8	1,96
6 L 70 MC	3,24	1	13 440	1	172,6	171,4	0,70
6 S 70 MC	3,82	1	15 420	1	171,2	168,3	1,69
6 L 55 GB	2,51	1	7 110	1	184,8	182,9	1,03
6 L 60 MC	3,24	1	9 900	1	173,9	173,1	0,46
6 S 60 MC	3,82	1	11 220	1	172,6	170,1	1,45
6 L 45 GB	2,67	1	4 680	1	186,1	183,3	1,50
6 L 50 MC	3,24	1	6 840	1	175,3	175,3	0,00
6 S 50 MC	3,82	1	7 860	1	173,9	172,1	1,03
6 L 42 MC	3,24	1	4 860	1	176,6	177,3	-0,40
4 L 35 GB	3,00	1	2 000	1	184,8	184,7	0,05
6 L 35 GB	3,00	1	3 000	1	184,8	182,2	1,41
9 L 35 GB	3,00	1	4 500	1	184,8	179,8	2,71
4 L 35 MC	3,00	1	2 240	1	179,3	184,0	-2,60
6 L 35 MC	3,00	1	3 360	1	179,3	181,5	-1,23
8 L 35 MC	3,00	1	4 480	1	179,3	179,8	-0,28
4 S 26 MC	3,77	1	1 460	1	177,0	182,2	-2,94
6 S 26 MC	3,77	1	2 190	1	177,0	179,7	-1,52
8 S 26 MC	3,77	1	2 920	1	177,0	178,0	-0,56
4 RTA 58	2,93	1	6 360	1	175,3	178,4	-1,77
9 RTA 38	2,89	1	6 120	1	180,7	179,0	0,94

Tab. 2. Comparison of the catalogue - b_{KAT} and calculated - b_{MEO} values of the specific fuel oil consumption of the low-speed marine diesel engines of SULZER make at all characteristic points of the permissible layout area, [g/kWh]

	ENGINE TYPE	$\frac{S}{D}$	N_{MCR} kW	n_{MCR} obr/min	R1 $\alpha=1$, $\beta=1$ $N=N_{MCR}$ $n=n_{MCR}$		R2 $\alpha=0,55$, $\beta=1$ $N=0,55 N_{MCR}$ $n=n_{MCR}$		R3 $\alpha=0,72$, $\beta=0,72$ $N=0,72 N_{MCR}$ $n=0,72\ n_{MCR}$		R4 $\alpha=0,55$, $\beta=0,72$ $N=0,55 N_{MCR}$ $n=0,72\ n_{MCR}$	
					b_{KAT}	b_{MEO}	b_{KAT}	b_{MEO}	b_{KAT}	b_{MEO}	b_{KAT}	b_{MEO}
SERIA RTA-2	4 RTA 84 C	2,86	15 280	100,0	171,2	173,9	163,2	166,9	170,2	174,4	165,2	169,1
	12 RTA 84 C	2,86	45 840	100,0	171,2	167,6	163,2	160,6	170,2	168,2	165,2	162,8
	4 RTA 72	3,47	10 960	94,0	171,2	171,2	163,2	164,2	170,2	171,7	165,2	166,3
	8 RTA 72	3,47	21 920	94,0	171,2	167,3	163,2	160,3	170,2	167,8	165,2	162,4
	4 RTA 52	3,46	5 680	130,0	173,9	175,1	165,9	168,1	172,9	175,6	167,9	170,2
	8 RTA 52	3,46	11 360	130,0	173,9	171,0	165,9	164,0	172,9	171,6	167,9	166,2
SERIA RTA-8	4 RTA 84	2,86	14 000	95	171,2	174,5	165,2	167,5	170,2	175,0	165,2	169,6
	12 RTA 84	2,86	42 000	95	171,2	168,1	165,2	161,1	170,2	168,7	165,2	163,3
	4 RTA 58	2,93	6 680	134	175,3	178,1	169,3	171,1	174,3	178,6	169,3	173,2
	9 RTA 58	2,93	15 030	134	175,3	173,3	169,3	166,3	174,3	173,9	169,3	168,4
	4 RTA 38	2,89	2 720	196	180,7	184,0	174,7	177,0	179,7	184,5	174,7	179,1
	9 RTA 38	2,89	6 120	196	180,7	179,0	174,7	172,0	179,7	179,6	174,7	174,2

Tab. 3. Comparison of the catalogue -b_{KAT}* and calculated -b_{MEO} values of the specific fuel oil consumption of the low-speed marine diesel engine of MAN-B&W make at all characterisic points of the permissible layout area, [g/kWh]

ENGINE TYPE	$\frac{S}{D}$	N_{MCR} kW	n_{MCR} obr/min	L1 α	L1 β	L1 b_{KAT} g/kWh	L1 b_{MEO} g/kWh	L2 α	L2 β	L2 b_{KAT} g/kWh	L2 b_{MEO} g/kWh	L3 α	L3 β	L3 b_{KAT} g/kWh	L3 b_{MEO} g/kWh	L4 α	L4 β	L4 b_{KAT} g/kWh	L4 b_{MEO} g/kWh
6 K 90 MC	3,00	22 800	82	1	1	171,2	170,2	0,8	1	164,4	167,1	0,821	0,817	171,2	170,5	0,655	0,817	164,4	166,7
6 L 90 MC	3,24	22 260	74	1	1	171,2	168,5	0,8	1	164,4	165,4	0,819	0,824	172,1	168,5	0,658	0,824	164,4	165,1
6 S 80 MC	3,82	20 100	77	1	1	171,2	166,8	0,8	1	164,4	163,7	0,821	0,818	171,2	167,0	0,657	0,818	171,2	163,5
4 S 26 MC	3,77	1 460	250	1	1	177,0	182,2	0,8	1	171	179,1	0,849	0,848	177	182,1	0,679	0,848	171	178,9
7 S 26 MC	3,77	2 555	250	1	1	177	178,8	0,8	1	171	175,7	0,849	0,848	177	178,8	0,679	0,848	171	175,5
8 S 26 MC	3,77	2 920	250	1	1	177	178,0	0,8	1	171	174,9	0,849	0,848	177	178,0	0,679	0,848	171	174,7

The b_{KAT} values relate to a constant ship's speed (propeller curve has not been accounted for).
The engines of the MCE series have not been included for defining the b_{MEO} formula.

*) In compliance with the technical data published in Project Guide for Two-stroke Engines, MC Programme, Edition 1, MAN-B&W 1985.

Appraised by prof.dr hab.inż. Roman Smolka