Journal of KONES Powertrain and Transport, Vol. 25, No. 2 2018

sciendo

ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2798

EXPERIMENTAL RESEARCH ON INFLUENCE OF THE FUEL NOZZLE GEOMETRY ON THE FUEL CONSUMPTION OF THE MARINE 4-STROKE DIESEL ENGINE

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Abstract

The article presents experimental research that has been carried out on a marine, 4-stroke, 3-cylinder, turbocharged engine. During testing, the engine operated at a constant rotational speed of 750 rpm and a load from 0 kW to 280 kW. The engine was fuelled by diesel oil of known specification and loaded by electric generator with water resistance. The fuel consumption was measured during the engine operation with fuel nozzles with different geometries. The measurement of the fuel consumption was carried out using a weighing system that was designed, constructed, and manufactured by the "KAIZEN" scientific research team at the Faculty of Mechanical Engineering at the Gdynia Maritime University. The results of measurements show changes in the fuel consumption by the engine with the geometry of the injected fuel spray. The research facility is Sulzer's 3-cylinder, 4-stroke, turbocharged AL25/30 piston engine. The fuel system consists of Bosch injection pumps controlled by a rotation speed regulator. Fuel injectors are centrally located in the cylinder heads of the engine.

Keywords: *marine engine, fuel consumption, fuel injection, experimental measurements, compression ignition engine*

1. Introduction

Piston engines are used on ships for main propulsion and for supply electric power generators. They are usually turbocharged 4- or 2-stroke Diesel engines with direct injection, In-Line, or V-type. It is estimated [1] that about 50% costs of the marine transport represents the costs of fuel consumption. This value depends on weather conditions, the ship speed, construction, and technical condition of the ship. In many cases, the cost of fuel consumption largely exceeds cost of maintaining and cost of crew. As a result of this, a significant area of scientific research is the possibility of limiting the fuel consumption by improving the structure of the marine equipment including internal combustion engines, but also by improving the organization of ship cruises and fleet management. It should be noted, that the fuel is the substrate in the chemical reactions of the combustion process, the product of which is the exhaust gas in the form of a mixture of chemical compounds. These compounds, in particular oxides of carbon, sulphur and nitrogen, as well as unburned hydrocarbons, soot and particulate matters, are not neutral for environment. One way to improve the engine efficiency and thus reduce the fuel consumption is to improve the combustion process in engine cylinders by adjusting parameters of fuel injection into the cylinder. These parameters are mainly pressure, temperature, and quantitative characteristics of fuel injection into the cylinder. They are determined by the construction of the injection equipment including the fuel spray geometry. In marine engines, fuel injectors with multi-hole nozzles are used controlled in a mechanical or electromagnetic manner (common rail systems). In general, the increase of the diameter of the fuel nozzle holes, the decrease of fuel injection pressure, the increase of the back pressure (the pressure in the engine cylinder at the time of the fuel injection) causes the decrease of fuel tip penetration, the increase of the fuel spray cone angle and the increase the Sather's mean diameter of fuel droplets [2-4]. This causes, among other things, a delay of fuel auto-ignition. The values of angle measured between the axes of the nozzle holes have to be selected according to the shape of the combustion chamber [5], while the number of holes is determined among the others by the efficiency of the fuel injector. These parameters of the fuel spray geometry should be optimized in terms of the fuel consumption and the emission of toxic compounds into the atmosphere for the entire ranges of load and speed of engine. It should be noted that the measurement of the fuel consumption on ships and on-road transport is technically complex and very often inaccurate.

Generally, there are 3 types of direct fuel consumption measurement methods [6]: volume, flow, and mass. The volume method consists in periodically measuring the fuel level difference in fuel tanks. In the case of marine installations, it consists in periodic probing of fuel levels in bunkers, circulating and sediment tanks. This method is widespread especially on older vessels and requires additional calculations related to the thermal expansion of the fuel. This method is characterized by very low accuracy due to the possibility of rocking the ship, the complex shape of the tanks and the possibility of their deformation. The modified form of this method is the use of a dedicated tank that allows accurate volume measurement. This system, along with a mechanical ship rocking neutralizing system, was successfully used on the STS Pogoria ship [7]. Flow methods consist in direct measurement of the volume of fuel flowing into and out of the engine. The result of the measurement is the fuel flow difference, and in this case, the thermal expansion of the fuel must be taken into account. The drawback of this method is the measurement inaccuracy associated with significant pressure pulsations in the fuel system before and after the engine. According to [8] the measurement error of this method is 2% for the compression ignition engine installed in the tractor. Key in this method is the use of flowmeters, which allow you to measure the flow of liquids with high-pressure pulsations (e.g. screw or Coriolis flowmeters). The third method of measuring fuel consumption is to measure the mass difference of the measuring tank or, in the case of high measuring tanks, measuring the hydrostatic pressure differential around the bottom of the tank. Mass measurement eliminates the need to calculate fuel density changes with temperature, but it is necessary to separate the measuring system from vibration and vibration caused by the engine, so these methods are usually used in stationary systems and laboratory systems. A separate group of measurement methods and technically accession of the fuel consumption are computational methods, based on mathematical models. Generally, methods based on white, black and grey boxes are used. White box models are based on calculations of actual phenomena occurring in an internal combustion engine, in only cylinder only, or the entire vehicle, or a machine driven by that engine. Black box models contain simplified math equations that approximate the phenomena occurring in the system in question. An example of such a solution is to calculate the fuel consumption based on the position of the fuel dado rail. Intermediate solutions are grey box [9]. A more detailed description of the models can be found in [10]. The aim of the study is therefore to determine fuel consumption of diesel engine and construction used in shipbuilding for chosen one for construction of fuel nozzles. The fuel consumption value was determined based on of direct measurement using a mass measurement system. Therefore, the additional purpose of the work is to test the efficiency and accuracy of measurement of fuel consumption of the measuring system, constructed and manufactured by the "KAIZEN" scientific research team at the Faculty of Mechanical Engineering at the Gdynia Maritime University.

2. Experimental procedure

The research facility is Sulzer's 3-cylinder, 4-stroke, turbocharged AL25/30 piston engine with the parameters shown in Tab. 1. The fuel system consists of Bosch injection pumps controlled by a rotation speed regulator through fuel dado rail and multi-hole fuel injectors, mechanically adjustable with use opening pressure of the injector. Fuel injectors are centrally located in the cylinder heads of the engine. The engine is installed at the Gdynia Maritime Shipyard Laboratory, and it operates at a constant rotational speed of 750 rpm. The load on the test engine is a generator, electrically connected to the water resistance.

Tab. 1. AL25/30 engine parameters

Parameter	Unit	Value
Rotational speed	rpm	750
Cylinder number	–	3
Cylinder diameter	mm	250
Stroke	mm	300
Compression ratio	–	12.7
Fuel nozzle opening pressure	MPa	25
Injection timing	º before TDC	18

During the tests, the engine worked with loads determined by the electrical output power from an alternator coupled motor with a motor value of 280 kW to value neutral gear in the 20 kW interval. Recording of measurement results was done under quasi-fixed conditions (change of exhaust gas temperature measured behind the turbocharger is not greater than 1 K/min). Three observations were made during the operation of the variable geometry fuel nozzle installed on all engine cylinders. Parameters of used fuel nozzles are presented in Tab. 2.

Tab. 2. Fuel nozzles parameters

Nozzle	Nozzle 1	Nozzle 2	Nozzle 3
Holes number	9	8	9
Holes diameter [mm]	0.325	0.375	0.320
Nozzle holes angle [º]	150	158	158

3. Fuel consumption measurement system

Fuel consumption measurement system has been build using dedicated components of Siemens weighing system, standard components of industrial automation and own design mechanical construction. Fig. 1 presents this system and describes it is main components.

Operating principle is based on weight measurement of the measurement tank before and after measurement, difference calculation, and fitting to the set measurement time. At first stage of measurement initiation, the system cuts-off fuel inlet valve from the main tank and opens fuel supply from the measurement tank, which is hanged on three weighing cells. Signals from the weighing cells are transferred to the Siwarex weighing module, where are filtered and analysed. Measurement tank is weighed in on-line mode and both weights before and after measurement are saved. After measurement, program calculates amount of the consumed fuel for the given measurement time. Result of the measurement and indirect data are shown on the control panel accordingly in kg/h and kg.

Accuracy of the measurement and the result depends on many factors. The whole system has been build basing on dedicated components of the renowned producer, accordingly to the all guidelines. Therefore, it should be assumed that the accuracy of the mass measurement results from the declared accuracy of the load cells. Accuracy data is shown in Tab. 3.

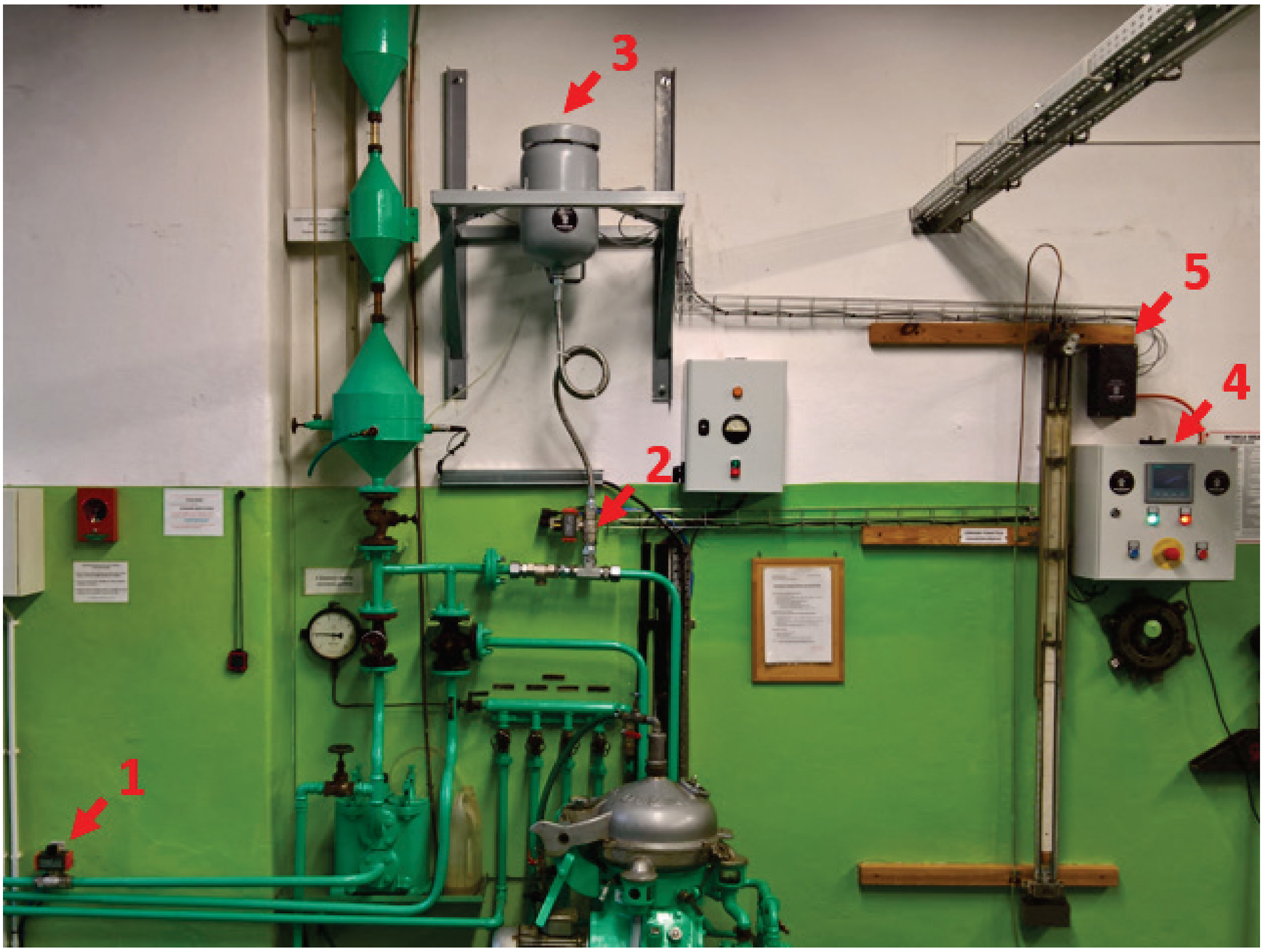

Fig. 1. Automated fuel consumption measurement system: 1 – main fuel tank cut-off valve, 2 – measurement tank cut-off valve, 3 – measurement tank, 4 – control cabinet, 5 – sensor connection box

Tab. 3. Parameters of the measurement system components

Component type	Load cell	Weighing module
Description and producer	WL260, Siemens	Siwarex WP231, Siemens
Accuracy class/ /declared accuracy	C3 (3000d, 3rd accuracy class)	0.05%, measuring frequency 100 Hz (10 ms)
Output signal	2 mV/V ±0.2 mV, exact value declared for each sensor with accuracy of 0.001 mV/V	MODBUS RTU Protocol, Ethernet
Nominal load of the cell	50 kg	N/A

The remaining elements influencing the accuracy of the measurement are operating conditions, adjustable measurement time, and possible interference effects such as vibration and possible inductive current in the load cell cables, which may be inducted near the generator. The development of algorithms that detect and filter the magnitude of these interferences is part of the current research.

4. Results

The measurement system of the fuel consumption constructed and manufactured by the "KAIZEN" scientific research team at the Faculty of Mechanical Engineering at the Gdynia Maritime University allowed to collect measurement data, which was presented in the form of average arithmetic mean values from all considered observations.

Figure 2 shows the fuel consumption characteristics in kg/h as a function of engine load. According to the results shown, the increase in the engine load causes an obvious increase in fuel consumption for each of the tested nozzles. It should be noted that the differences in fuel consumption values for individual nozzles are negligible. For the maximum load, the lowest consumption was observed for the nozzle 3, which was 1.8 kg/h less than the value obtained for the nozzle 2. This represents a 2.5% change. During operation of the engine with a relatively low load observed changes in fuel consumption fall within the measurement error limits.

Figure 3 shows the calculated Specific fuel consumption values. According to the results presented, changing the engine load causes changes in Specific fuel consumption. For each fuel nozzle tested, fuel consumption is greatest for the lowest engine load. From the measurements, it can be seen that these values decrease as the load increases, while the operation of the motor with a load greater than 160 kW does not cause significant changes in the motor efficiency.

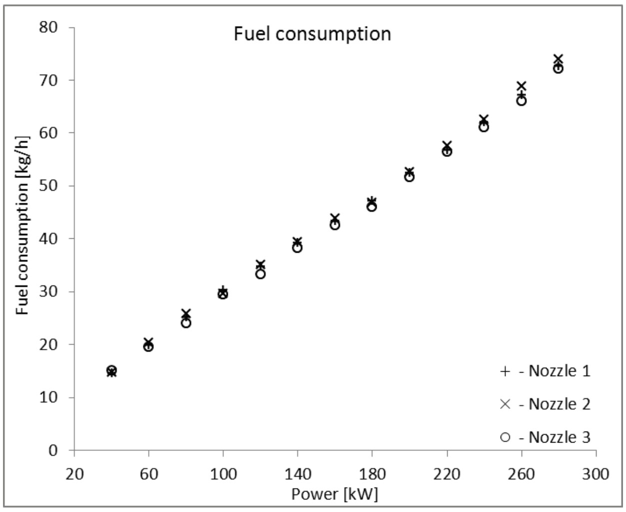

Fig. 2. Characteristics of fuel consumption

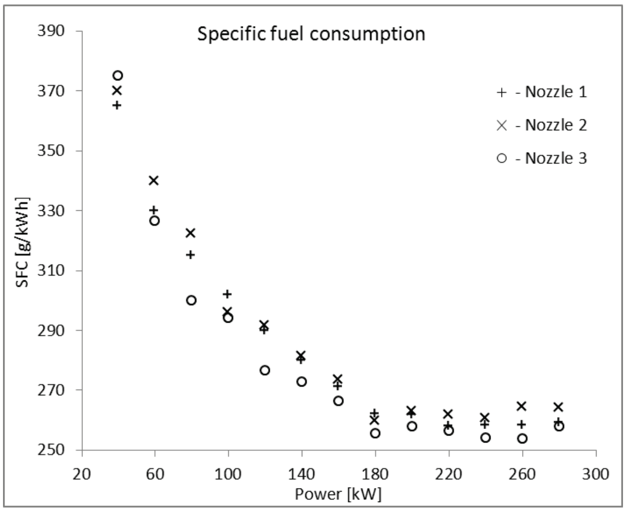

Fig. 3. Specific fuel consumption

The results show fuel consumption changes by the AL25/30 engine with a change in fuel stream injection geometry. The use of nozzles 3 is most advantageous. During operation of the engine with these nozzles, the fuel consumption was the smallest for the whole load range of the engine. The smallest efficiency was observed during the operation of the nozzles 2. In this case, the unit fuel consumption was on average 2.8% higher than that of the spray nozzle 2 for the entire range of engine load involved. According to the presented results, choosing the right fuel injector geometry for the shape of the combustion chamber is important because it helps to reduce the cost of engine operation. It should also be noted that the final assessment of the geometry of the fuel nozzle should be supported by an analysis of the combustion process and the assessment of the impact on the emission of harmful compounds into the atmosphere. According to the results [11], reducing the diameter of the injector holes and increasing the number of holes facilitates the intensification of the fuel spraying and evaporation process. For this reason, after the combustion of fuel the burning process is more turbulent. This results in an increase in the temperature and pressure of the combustion process, which helps to reduce fuel consumption.

5. Conclusions

Laboratory studies were designed to test the load cell system for measurement of fuel consumption and to investigate the effect of the geometry of the fuel injectors on the fuel consumption value. The results showed that in terms of fuel economy, the best solution is to use spray nozzles 3. These are spray nozzles with the largest number of holes, the smallest diameter of the holes and the largest cone angle of injection. Reducing the diameter of the holes is conducive to the intensification of the process of spraying and evaporating the fuel. As a result, the burning process is faster. The alleged effect is an increase in the temperature and pressure of the combustion process, but this conclusion has to be taken with high reserve due to the lack of measurement data. Use of the sprayer 2 caused an increase in specific fuel consumption by an average of 2.8%. This injector had the largest diameter of the holes and the smallest number of them in all investigated spray nozzles geometry.

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Manuscript received 07 March 2018; approved for printing 27 June 2018