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Combustion of LPG/DME gas mixtures in an SI engine with correction of the ignition advance angle

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The paper presents the results of tests on a SI engine fueled with an LPG/DME blends of various composition. A number of experimental studies and calculations using a mathematical model were carried out to examine the suitability of this fuel. These tests allowed for the analysis of the changes taking place in the combustion process and the assessment of the main operating parameters of the engine. The engine was powered by an LPG/DME fuel mixture with different proportions of components. The share of DME ranged from 0% to 30% of the fuel mass. The obtained results reflect the operation of the engine in the full load range and selected rotational speeds. Measurement series were made for different settings of the ignition advance angle. Based on the obtained results, a corrected map of the ignition advance angle was developed. The obtained results confirm the usefulness of using the LPG/DME mixture to power the SI engine.

Key words: *LPG/DME, fuel blend, combustion, SI engine*

1. Introduction

One of the main directions of energy transformation in the global economy is the increase in the use of renewable fuels. Dimethyl ether (DME) is a real part of this strategy because it has favorable physical and chemical properties and can also be obtained using renewable energy sources [15]. Research results published in recent years show DME as a modern fuel, both in diesel engines [3, 6, 14, 16, 17] and in SI engines as an addition to LPG [4, 13, 18].

Features of modern fuel include the possibility of a significant reduction of PM and NO_x emissions in a diesel engine [12]. Tests of LPG/DME mixtures also confirm the possibility of meeting the applicable exhaust emission standards in a car with an SI engine, while maintaining similar traction properties [5, 11]. The results of the conducted research indicate the possibility of increasing the share of DME in the mixture to 30% by weight. Such fuel can also be used in liquid-phase injection power systems [1].

The superior attribute of this fuel is the fact that it can be an element of the fuel chain based on the use of so-called green hydrogen [13]. In this system, DME is a product made using H_2 and CO_2. The main attribute is obtaining a high-energy fuel, the storage and distribution of which is much less energy-intensive than in the case of hydrogen. In addition, there is also the possibility of reusing the emitted CO_2 [10]. Due to the above aspects, research on the use of DME in various branches of the economy is intensively conducted. Therefore, the use of DME as a fuel requires a thorough knowledge of the combustion process and its products in relation to the performance parameters of the engine [2, 9, 19].

The above aspects motivate to carry out research with this fuel and to analyze the combustion process. Contrary to the published test results, the scope of this study also includes measurements made at partial engine loads. This scope of the experiment is much more in line with real engine operation in road conditions.

2. Experimental studies

2.1. Measurement set-up

The popular passenger car powered by a 1.6 liter engine, naturally aspirated with a compression ratio of 9.6, port fuel injection, two valves per cylinder, flat pistons and without external EGR was used in the experiments. The experiments were performed on a MAHA MSR500 chassis dynamometer. The main features characterizing the engine installed on the tested vehicle have been listed in Table 1. Engine performance has been estimated on the basis of acquired dynamic characteristics, defining the power on wheels in the function of vehicle speed. The test stand has been equipped with various transducers and sensors allowing the identification of engine operating conditions. Basic measurements and control systems allowed continuous acquisition of engine operating conditions, through registrations of:
- in-cylinder pressure
- crank angle, with the TDC identification
- power on wheels
- manifold pressure
- inlet air temperature
- exhaust gases temperature
- fuel mass flow to the engine.

Table 1. Engine specification

Parameter	Value
Engine code	X16SZR
Cylinder number and layout	4 R
Maximum power	55 kW@5200 rpm
Maximum torque	128 N·m @2800 rpm
Displacement	1598 ccm
Bore x stroke	79.0 × 81.5 mm
Compression ratio	9.6

The in-cylinder pressure was measured by Kistler 6121 piezoelectric pressure transducers and a charge amplifier, Kistler 5011A. The signals were processed in type NI PCI-

6143 board in a computer for online pressure measurements. The pressure recording system was also connected to the Kistler 2613B crank angle encoder giving the temporal resolution of the pressure recordings of 0.5 deg CA.

The pressure measurements were recorded and stored on a computer, with recordings performed for 150 subsequent cycles in each test, and were further processed with the help of a script debugged in LabView 7.1 environment.

Fig. 1. Tested car on dynamometer chassis

Fig. 2. Stand for preparing of LPG/DME blends

2.2. Methodology of research

The main purpose of the conducted research is to determine the effect of changes in the ignition advance angle on the basic parameters of engine operation using fuels with different DME content. The change of the ignition advance angle is carried out by introducing into the algorithm of the engine controller a set value correcting the angle determined by the controller. During the tests, two additional degrees of correction were applied, increasing the ignition advance by 3 and 6 degrees CA compared to the factory controller settings. For each measurement point, three measurements were made, one at the nominal ignition timing (without correction) and two more using the given correction values. The scope of the tests carried out included measurements in steady states of engine operation at selected rotational speeds and variable engine load. The following rotational speeds were selected for the tests: 2000, 2500 and 3000 rpm. The degree of engine load is equivalent to the width opening of the throttle (WOT). The test was performed for the following engine loads: 21, 33, 48, 60, 75, 90 and 100%.

3. Simulation studies of the combustion process

Experimental tests carried out on a chassis dynamometer allowed for the measurement of the most important operational parameters and, at the same time, for a detailed analysis of the combustion process involving DME mixed with LPG in various proportions. The basic parameter determining the possibilities of using DME is the power measured on the wheels of the vehicle. The IA correction carried out in the second series of tests revealed the possibility of increasing the power of the tested engine. The results of these measurements were presented in an earlier publication [8].

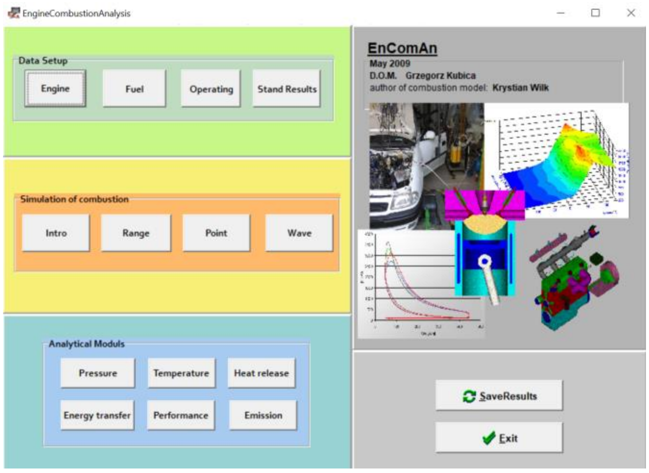

Fig. 3. The main form of the simulation program

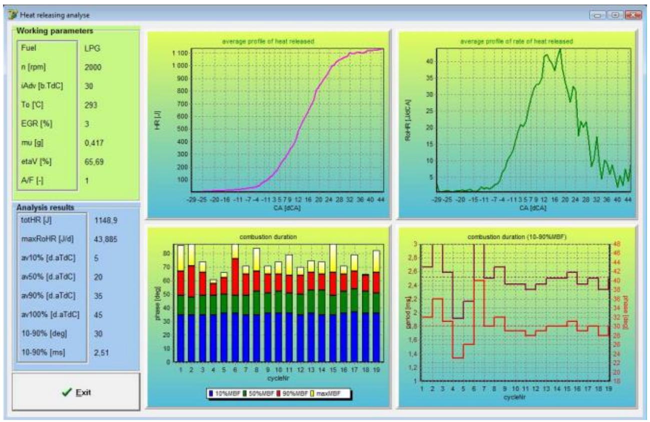

Fig. 4. One of the *EnComAn* calculation form

On the basis of the recorded experimental results, calculations of thermodynamic parameters characterizing the combustion process were performed. Simulation studies were performed using the *EnComAn* application (Fig. 3), which is a proprietary product. The program is designed for

comprehensive calculations of thermodynamic processes in the engine cylinder, using a mathematical model [7]. Simulation calculations are carried out on the basis of the course of pressure in the combustion chamber recorded in experimental tests (Fig. 4). The analysis of this signal allows to determine the so-called representative sample and perform statistical calculations of the indicated pressure. The *EnComAn* simulation program calculates a number of parameters describing the combustion process. These include:
– fresh charge and exhaust gas temperatures
– heat release in the combustion process
– current exhaust gas composition (including 10 components)
– heat transfer between the walls and gases in the combustion chamber
– engine operating parameters.

4. Discussion of the results

The addition of DME to LPG changes the composition of the fuel. The most significant change is the presence of oxygen in the DME molecule. This means that the need for oxygen-containing air to burn the load decreases. Providing oxygen in this form increases the efficiency of filling, which has a positive effect on the performance of the engine. The second important feature of DME is its ease of self-ignition, which is reflected in its high cetane number. Therefore, a detailed analysis of the course of the combustion process is important. The introduction of the correction of the ignition advance angle makes it possible to assess the possibilities of obtaining the best organization of this process, both in terms of the heat release function and the effects of its course. The corrected map of the IA angle settings is shown in the diagram (Fig. 5).

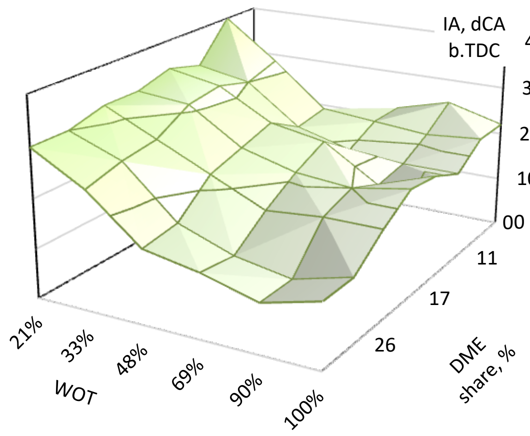

Fig. 5. Corrected map of IA angle, n = 3000 rpm [8]

The correction of the ignition advance angle ensures an increase in engine power in practically the entire engine load range. The indicated power at nominal IA settings is shown in the diagram (Fig. 6). The maximum values of the obtained power after IA correction are shown in the graph (Fig. 7), while the averaged trends of changes for all tested LPG/DME mixtures are shown in a separate graph (Fig. 8).

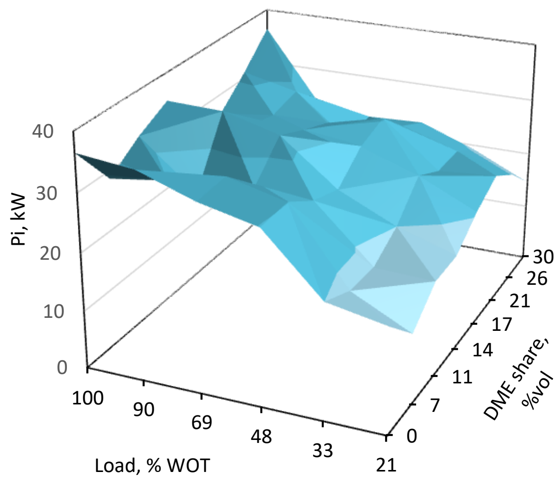

Fig. 6. Indicated power before IA correction, n = 3000 rpm

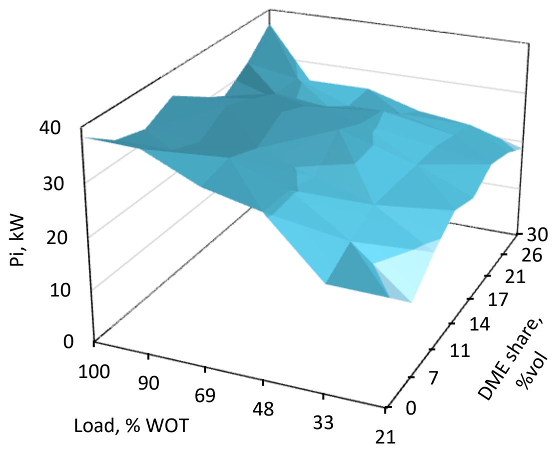

Fig. 7. Indicated power after IA correction, n = 3000 rpm

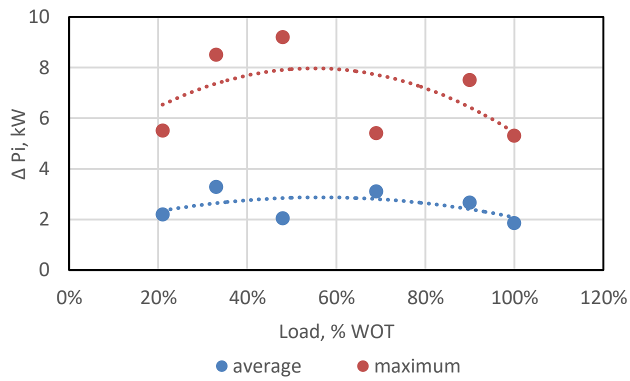

Fig. 8. Changes in indicated power, averaged for all tested fuel blends

As further results indicate, this is related to the amount of energy released in the combustion process, as HR changes in the entire range of tests show similar trends (Fig. 9 and Fig. 10). For all tested loads, there is a slight increase in this parameter (Fig. 11). These changes result rather from a greater dynamics of the charge exchange, because the IA settings do not directly affect the filling of the cylinder and the amount of fresh charge.

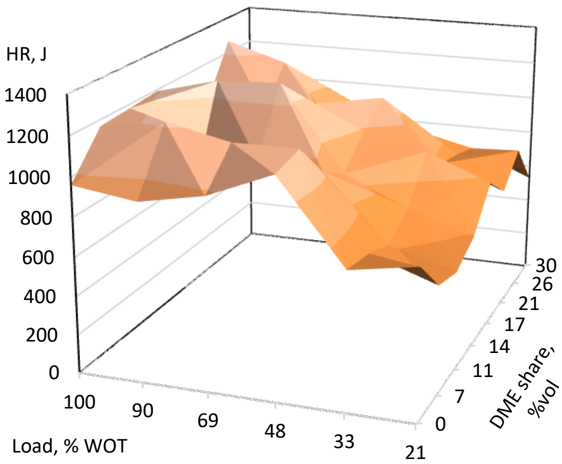

Fig. 9. Heat release amount before IA correction, n = 3000 rpm

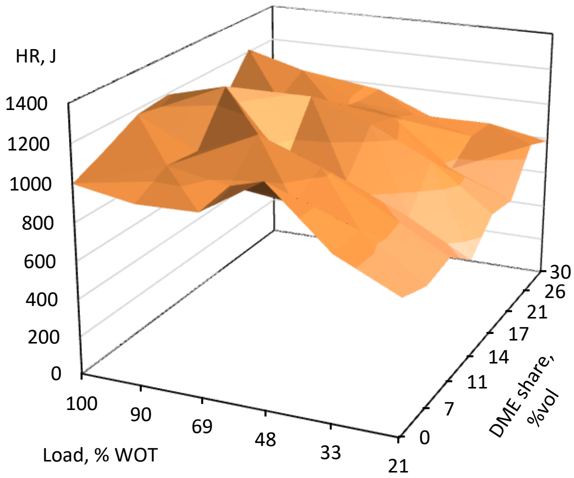

Fig. 10. Heat release amount after IA correction, n = 3000 rpm

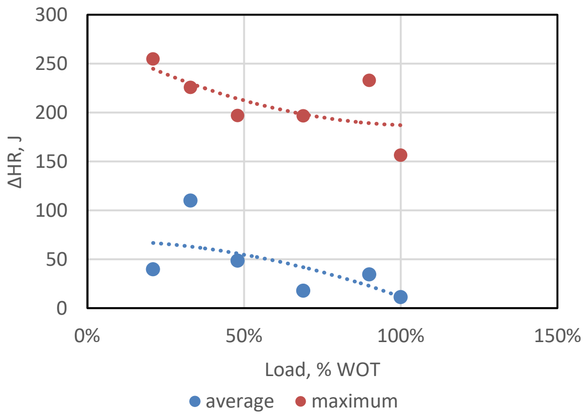

Fig. 11. Changes in HR, averaged for all tested fuel blends

The correction of the IA most strongly interferes with the nature of the combustion process, because it changes its correlation with changes in the pressure in the cylinder caused by the movement of the piston. This is also visible in the changes in the temperature of the gases in the combustion chamber (Fig. 12). The maximum temperature inside the cylinder chamber at nominal IA settings is shown in the diagram (Fig. 13). The area of greatest changes includes mixtures with a share of 7%, 11% and 14% DME. A clear increase in gas temperature occurs in the entire engine load range (Fig. 14).

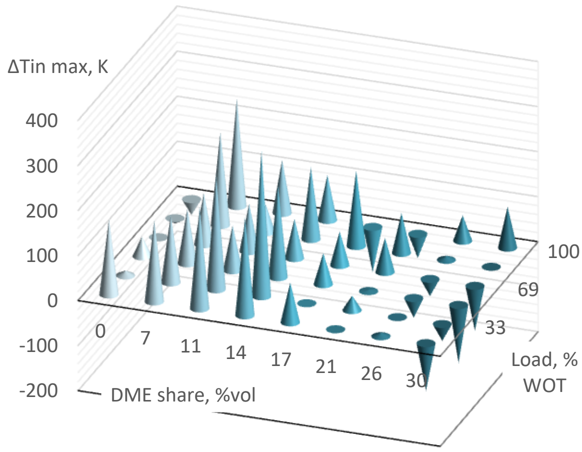

Fig. 12. Changes in the maximum temperature in the cylinder, n = 3000 rpm

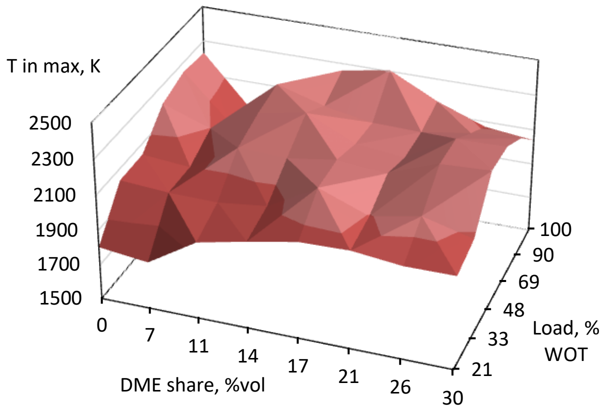

Fig. 13. The maximum gas temperature in the cylinder, IA nominal

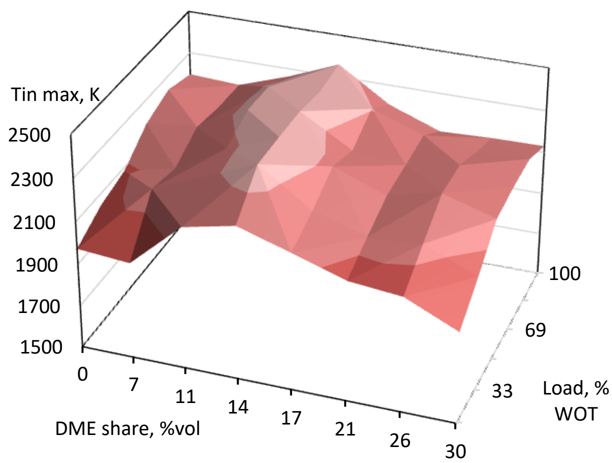

Fig. 14. The maximum gas temperature in the cylinder, IA corrected

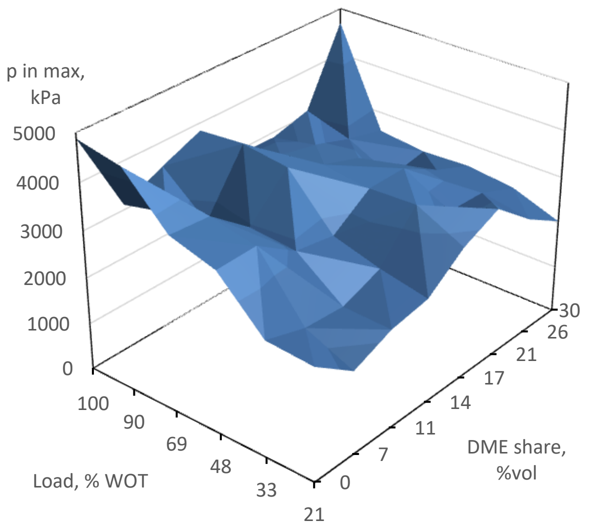

Fig. 15. The maximum in cylinder pressure, IA nominal

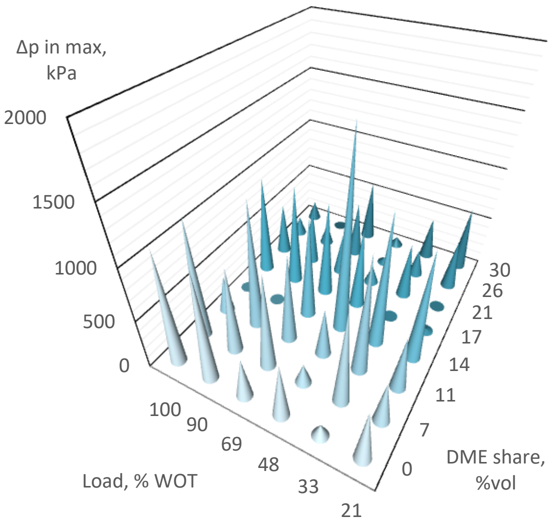

Fig. 16. Changes of the maximum in-cylinder pressure, n = 3000 rpm

The parameter that reflects the influence of all factors shaping the changes taking place in the engine cylinder is the indicated pressure. The maximum in-cylinder pressure for nominal IA settings is shown in the diagram (Fig. 15). The obtained measurement results show an increase in the pressure value practically throughout the entire range of tests (Fig. 16). Of course, the increase in pressure also results in an increase in engine performance, which is desirable. However, too high increase in pressure, especially caused by a rapid increase in dp/dφ, leads to loss of control over the combustion process and so-called burnout may occur. knocking combustion. The control parameter for such behavior is the standard deviation of the mean pressure indicated by COV_{imep}. The test results indicate that although in some operating states, there may be a greater non-repeatability of subsequent work cycles (Fig. 17), this increase is small, below 2%. The average values of changes in this parameter are negative in the entire load range, which indicates that the combustion process is generally stable and the repeatability of successive work cycles is greater.

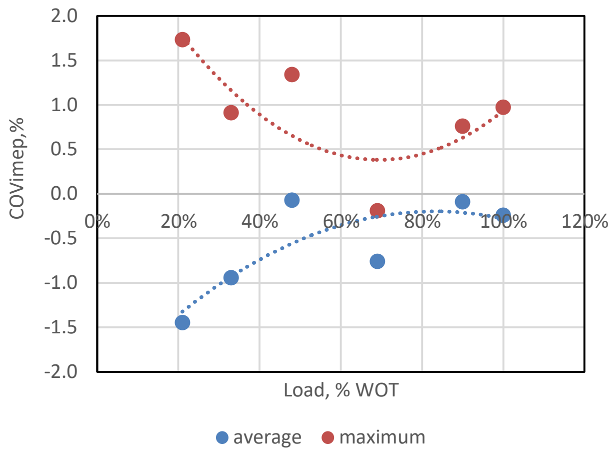

Fig. 17. Changes of value COV_{imep} after IA correction, averaged for all tested fuel blends, n = 3000 rpm

5. Conclusions

The course of the conducted tests and the analysis of the obtained results allow to conclude that:

1. The use of the DME additive in a mixture with LPG is, in terms of observation of dynamic parameters and the combustion process, a fully valuable and useful fuel that does not impair the performance of an engine fueled only with LPG.
2. Introduction of an additional correction of the IA angle, in relation to the factory settings, allows to obtain higher power values, on average by 3 kW (Fig. 6).
3. The correction of the IA does not significantly affect the total amount of HR in the engine's working cycle, but it improves the dynamics of the combustion process, which results in an increase in temperature and pressure in the cylinder. The highest increase in these parameters occurred for mixtures containing DME in the range of 7–14%. The temperature rise in this area is 80–100 K for all load levels tested.
4. The results of the measurements indicate higher values of the indicated pressure in the whole range of engine load changes, for all tested LPG/DME mixtures. However, the occurring pressure increases are not the result of disturbances in the combustion process, as evidenced by the calculated changes in COV_{imep} values.
5. Despite the fact that the results of published tests carried out in other centers show that the requirements of emission standards are met [5, 11] and the possibility of reducing CO_2 emissions [16], in the case of interference with the engine control parameters, it is necessary to carry out appropriate exhaust emission tests, to determine the total usability of this type of fuel.

Nomenclature

b.TDC	before top dead center	HR	heat released
CA	crank angle	IA	ignition advance
COV_{imep}	cyclic variation of indicating mean effective pressure	LPG	liquified petrolum gas
DME	dimethyl ether	PM	particulate matter
EGR	exhaust gas recirculation	SI	spark ignition
		WOT	width opening of the throttle

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