The problems of measuring the temperature of the small engines (SI) on the example of a drive for non-road mobile machines

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Abstract. Modern drive units designed for driving non-road machines are characterized by liberal regulations regarding the limits of toxic compounds emission in exhaust gases. These regulations contribute to the low level of technical advancement of this type of drive units. Among the new non-road small engines (SI) offered in the sale in 2018 in the European Union, the majority of them are equipped with carburettor systems whose fuel supply characteristics do not allow to achieve modern fuel-air mixture control standards. Therefore, action should be taken to develop these drive units towards electronic control of combustion processes in these engines, which will allow the use of innovative control algorithms. One of the basic signals supporting the selection of the air-fuel mixture is the engine temperature. The paper presents an overview of the methods for measuring the temperature of internal combustion engines and presents the results of research on the process of warming up the engine. The tests were carried out with three methods using an oil temperature sensor, a surface temperature sensor and a thermal imaging camera. An attempt was made to indicate construction guidelines taking into account the place of temperature measurement, correction factors were determined in relation to the oil temperature. The developed coefficients can be used to precisely determine the thermal state of the engine, which is an important aspect in the process of controlling the fuel-air mixture and affects its consumption.

Keywords: small engine SI, non-road mobile machines, engine temperature measurement

1 Introduction

Air pollution in recent years has become a serious environmental problem affecting people's health and lives [1-3]. Frequent exceeding the permissible limits of air pollution, especially in urban agglomerations [4-7], leads to trends limiting the emission of harmful factors in all branches of industry. Many years of efforts to limit emissions from internal combustion engines have led to a significant reduction in the production of unfavourable combustion

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products by this group of emitters. At the same time, it contributed to the significant technical development of these drive units. Electronic engine control enabled the expansion of the drive unit control function in relation to other aspects of the control system than just the injection-ignition system. The interchange ability of signals and the possibility of their use by various control units used in the vehicle made it possible to develop safety, comfort and vehicle traffic control systems that interact with each other. Another group of devices equipped with internal combustion engines are non-road work machines. The drive units of these machines are classified as small engines. They are characterized by relatively liberal pollution regulations [8, 9] and pose a serious ecological problem [10]. Lack of high requirements regarding the emission of air pollutants for manufacturers of this type of drive units leads to a low level of technical advancement of these engines. On the market in 2017 from among 900 models, small engines offered, up to 89% are drive units characterized by carburettor fuel supply system [11-12]. The lack of electronic control of the fuel supply system is characterized by a lack: sensors and actuators that can implement advanced control procedures of the drive unit and the entire machine. In order to achieve even higher environmental requirements by small engine engines, they will be equipped with electronic injection systems working with the use of control algorithms such as:

- "Speed Density" algorithm [13],
- the "Alpha-N" algorithm [13],
- algorithm of Wendeker M., Jakliński P., Czarnigowski J. [14],
- Myszkowski S. algorithm, corrected injection time, taking into account the known impact of selected values on the composition of the fuel-air mixture, that can additionally be extended by: the total and long-term impact of many variables or unknown quantities on the composition of the fuel and air mixture, which can also include 2 variables that result either from the correction of the regulation of the mixture in the closed loop, or from the regulation of the composition of the mixture in the open loop [15],
- the fuel dose control algorithm in the GDI engine (from Gasoline Direct Injection), described by Bartczak M., Wołczyński Z. [16].

A common feature of these algorithms is the use of the thermal state of the internal combustion engine in the process of determining the composition of the fuel-air mixture.

The introduction of an electronic injection system allows the development of multiple input control systems. One of the parameters about which the control procedure can be extended is the engine and oil temperature. These parameters have a large impact on energy losses and wear of the friction elements of the engine, affecting the minimization of the effects of friction. Due to the essence of the discussed parameter along with the evolution of combustion propulsion units in many fields of operation, various concepts of measurement and assessment of the thermal status of the internal combustion engine have been developed. The following temperature measurement can be distinguished:

- cooling liquid;
- oil;
- the surface of the engine components.

The measurement of the thermal state of the engine by measuring the temperature of the cooling liquid is the most commonly used signal in the algorithms controlling the operation of the engine. In addition, the oil temperature measurement is usually a control measurement aimed at signalling the exceeding of the acceptable temperature range. Another is the sensor for measuring the temperature of the engine components, most often used in air-cooled drive units. The classic air-cooled drive units were not equipped with an injection system, hence the temperature measurement did not affect the regulation of the composition of the mixture, which was regulated by the carburettor fuel system. There are no described solutions for controlling the injection system used in an air-cooled engine in the aspect of measurement and the influence of engine temperature on the composition of air-fuel mixture. The article presents the results of thermal tests of the engine at selected measuring points (oil sump, surface of the drive unit). An attempt was made to describe the temperature of the engine during warm-up by measuring other engine components than the oil temperature, determining the corrective coefficients. Control ideas have been developed to improve the operating conditions of the internal combustion engine when operating in the aspect of friction between the engine components by running the drive under load only after reaching the optimum oil temperature. The tests were carried out on a power unit manufactured in 2017 which is a common representative of the group of drives subject to the regulations of non-road mobile machinery [9, 17], whose disadvantage was the carburetted power system [18]. The unit has been modernized, and one of the results of the work are the results of thermal engine tests. The scheme of the developed and used injection-ignition system is shown in Figure 2.

2 Research methodology

The tests were carried out on a modernized German GX390 combustion engine cooled with air intended for driving crushing machines, whose driving units [19-24], gears and working members [25-26] are subject to testing and modernization enabling their parameters to be improved. To serve this purpose, this unit was equipped with a CLT (Coolant Temperature Sensor) temperature sensor (1) mounted in the head, which is a NTC (Negative Temperature Coefficient) thermistors characterized by a non-linear, decreasing resistance. as the temperature rises (Fig. 3) [27]. The second sensor is the Pt100 oil temperature sensor (2) placed in the oil sump, characterized by non-linear resistance as shown in Figure 1. The results were recorded by the ECU EMU Master [13] engine controller in the Ecumaster EMU CLASSIC Client program. In addition, the surface temperature of the engine was measured using the Seek Reveal Fast Frame XR thermal imaging camera, indicating the temperature measurement on the cylinder surface (3). Figure 4 indicates the places where the temperature by all three measuring devices is measured. The engine temperature change tests were carried out in the range from start-up, cold engine (about 20°C), to stabilize the temperature of all sensors, the temperature of the atmospheric air was equal to 20°C.

3 Research results

The characteristics of the external change of the cylinder temperature as a function of time were recorded using a thermo vision camera, as shown in Figure 7, together with thermal images of the engine. The specification of temperature characteristics from the CLT sensor installed in the engine head, the Pt100 engine oil temperature sensor installed in the oil sump and the cylinder temperature recorded by the thermal imaging camera are shown in Figure 5.

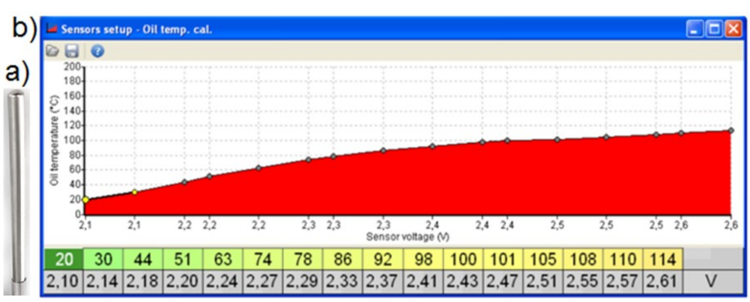

Fig. 1. Oil temperature sensor Pt100: a) view, b) characteristics of voltage changes under the influence of temperature

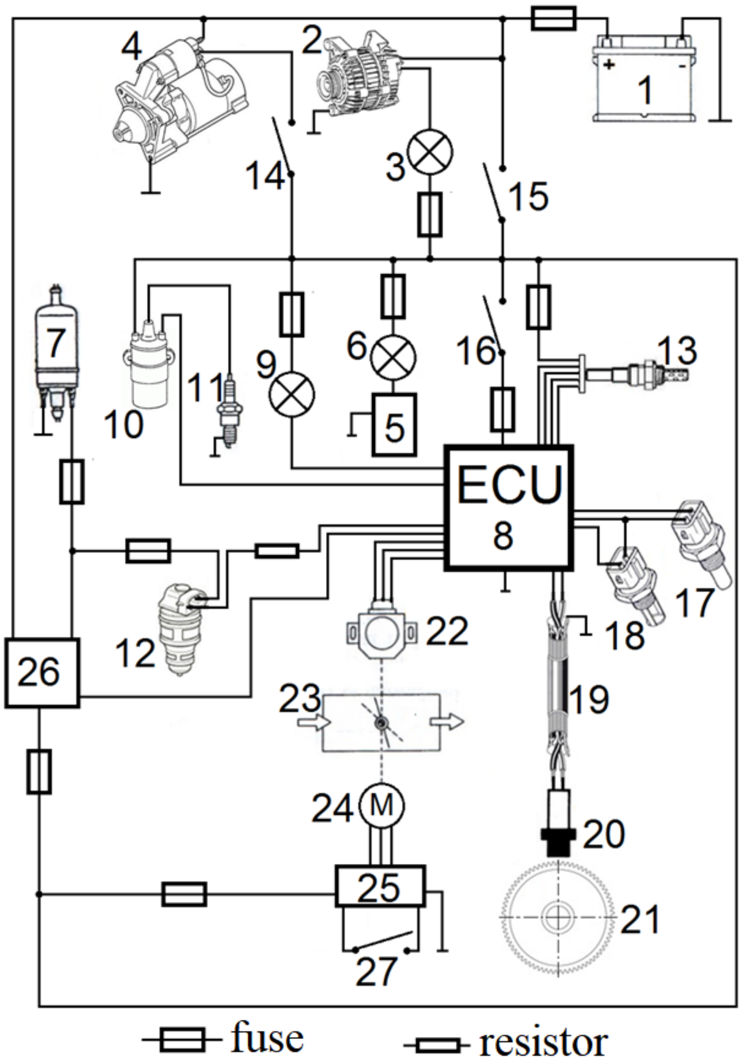

Fig. 2. Schematic diagram of the innovative injection-ignition system used in the German GX390 engine: 1 – 12V battery, 2 – 65A alternator, 3 – charging indicator light, 4 – starter, 5 – oil level sensor, 6 – oil level control lamp, 7 – electric fuel pump, 8 – electronic control unit, 9 – malfunction indicator light MIL, 10 – high-voltage ignition coil, 11 – spark plug, 12 – injector, 13 – wide oxygen sensor in the exhaust gas, 14 – starter switch, 15 – circuit switch, 16 – emergency switch, 17 – engine temperature sensor, 18 – temperature sensor of intake air, 19 – shielded cable, 20 – speed sensor and engine crankshaft position, 21 – pulse wheel, 22 – throttle position sensor (TPS), 23 – throttle valve, 24 – servomechanism, 25 – servo controller, 26 – fuel pump and injector relay, 27 – manual engine speed switch

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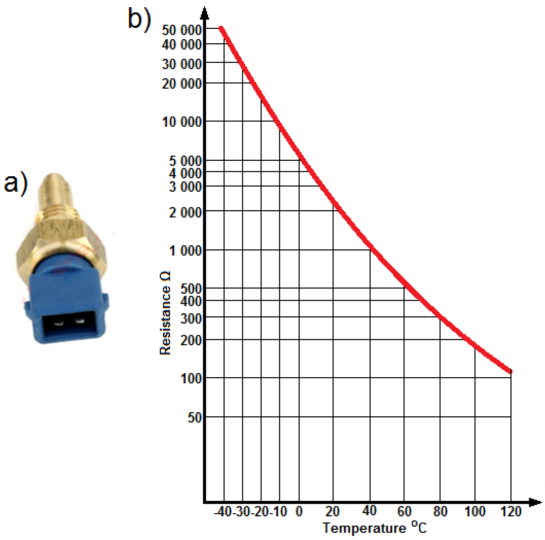

Fig. 3. CLT engine temperature sensor: a) view, b) characteristics of resistance changes under the influence of temperature [27]

Fig. 4. Test stand, chopper with modernized German GX390 engine: 1 – engine head temperature sensor CLT, 2 – Pt100 oil temperature sensor, 3 – area for which the value from the camera is indicated on the display

4 Analysis of results

The engine temperature recorded by the CLT sensor and the thermal imaging camera is similar, and its value on the cylinder surface increases with a few seconds delay compared to the temperature in the engine head. After thermal stabilization of the tested measuring points, the temperature on the cylinder surface is 3°C lower than in the engine head and the oil temperature is lower by 19°C (Fig. 5). Indications from the CLT sensor showed the highest temperature during the whole heating process. It can be due to the fact that the sensor is mounted the closest to the heat source, which is near the combustion chamber. At this point, the change in temperature is also detected first. Another place where the temperature change is recognized is the surface of the cylinder, on which temperature changes are observed 10 sec later than during the temperature measurement of the head. The third measuring point, which is the oil temperature, starts the thermal change 188 sec later than the observed temperature changes in the engine head. The obtained temperature-time functions describe the sixth order polynomials indicated in Figure 6. The results of the conducted research indicate that the change in temperature as a function of time of the researched measurement points leads to the achievement of various arguments and function values while maintaining a similar shape of the function.

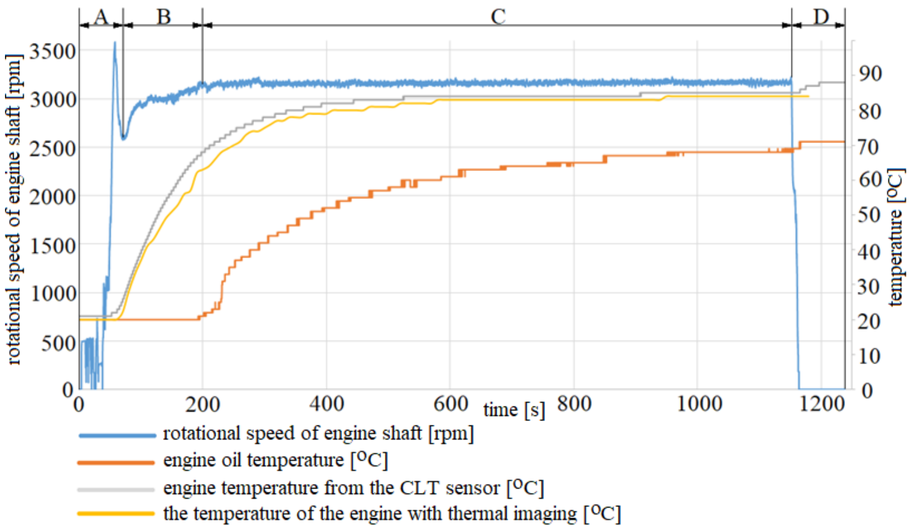

Fig. 5. Characteristic of engine temperature changes as a function of time depending on engine rotational speed shaft, where: A – engine start, B – speed stabilization, C – constant speed operation, D – engine shutdown

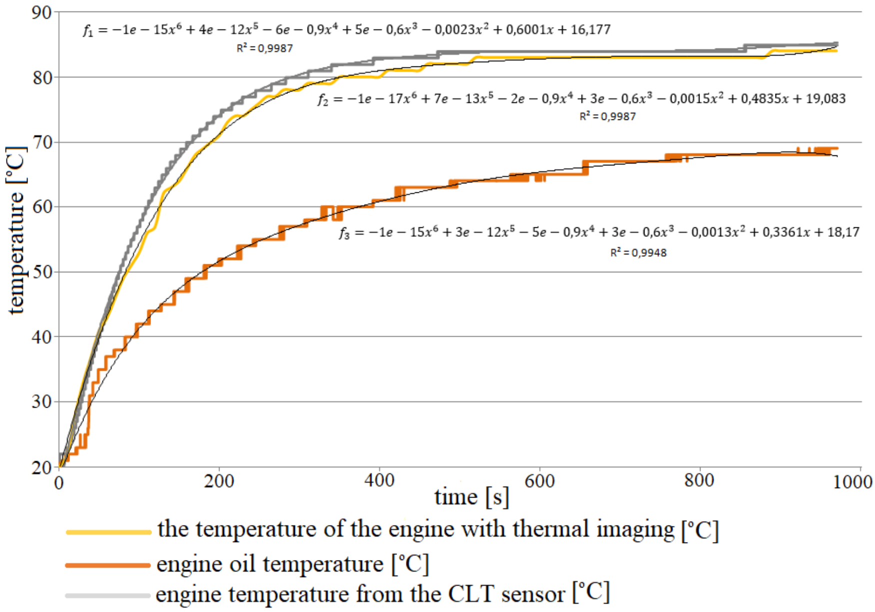

Fig. 6. Heating temperature of selected measurement points as a function of time

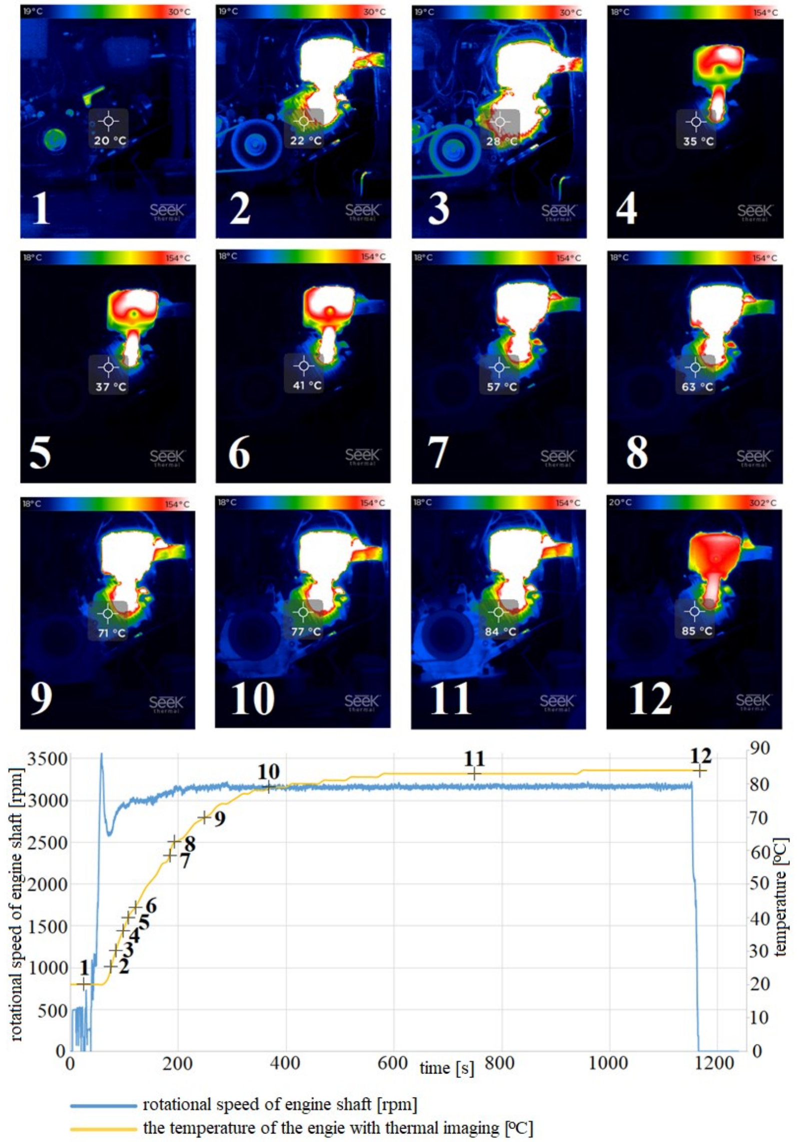

Fig. 7. Characteristic of engine temperature changes as a function of time recorded with a thermo vision camera, with indication of temperature on the engine cylinder

The optimum oil operating temperature ranges from 85°C to 105°C [28]. It is therefore necessary to aim, when operating the device, for work when the oil temperature is within the limits of the oil flow temperature indexes, i.e. the viscosity index at low and high temperatures and operation in the optimum oil temperature range during exploitation. In car engines, the cooling system is implemented mainly by electrically controlling of the fan. In the engine under test, the fan propellers are mounted on the crankshaft without adjustment possibility. Changing the engine cooling possibility in such a system varies with the change in the operating state of the engine, by changing the rotational speed. The preliminary studies presented in Figure 6 indicate that the engine temperature increases after decreasing the rotational speed (section D). The reason for this phenomenon is to reduction of the air flow cooling the engine.

During the thermo vision camera research, attention was paid to the tested surfaces, which could have introduced an error in the interpretation of the results. On glittering surfaces (Fig. 8), the temperature of objects reflecting on them was visible. Selected surfaces introducing error by reflection of images were not included in the conducted analyzes.

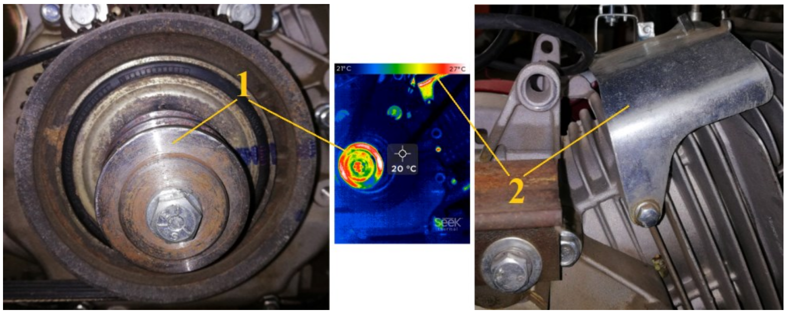

Fig. 8. Examples of machine parts introducing a measurement error: 1 – pulley, 2 – cylinder cover

5 Control system concept

The developed control concept will be presented on one of the modern fuel-air mixture control algorithms. The "Alpha-N" algorithm, which is used in engines without a stable vacuum in the intake manifold, i.e. in single-cylinder engines and the tested power unit after modernization, is characterized by the correction of the fuel dose during engine start-up. The algorithm used together with dedicated software makes it possible to regulate the injection time during start-up e.g. in the scope of:
- definition of the injection time function depending on the engine temperature (in the classic engine coolant temperature);
- definition of the injection time correction function depending on the percentage of throttle deflection;
- definition of delivery of a single fuel dose prior to synchronizing the ignition system;
- definition of the combustion chamber cleaning option from excess fuel;
- definition of work in injectors during start-up in a sequence or group.

This algorithm is described in the form of equation 1, where the introduced corrections are contained in the fuel dose correction variable C:

$$t_w = I_{const} \cdot VE_{(TPS,rpm)} \cdot AD \cdot C + AE + I_{OT} \,, \qquad (1)$$

where:
t_w – injector opening time signal,
I_{const} – constant determining the injector opening time required to obtain a stechiometric mixture (λ=1) with a given injector size and engine capacity, pressure 100 kPa, suction air temperature 21°C and 100% of the volumetric efficiency value, read from the engine load characteristics and speed,
$VE_{(TPS,rpm)}$ – value of volumetric efficiency read from the load characteristic of engine and rotational speed,
AD – percentage difference between air density and air density at 21°C,
C – fuel dose correction,
AE – enrichment when accelerating,
I_{OT} – time between the moment of applying the voltage to the injector coil and the moment of fuel injection.

The percentage value of the fuel dose correction C may depend on many variables according to Equation 2 :

$$C = B \cdot W \cdot ASE \cdot EGO \cdot KS \cdot IAT \,, \qquad (2)$$

where:
B – barometric correction,
W – value of enrichment of the mixture as a function of coolant temperature expressed in percent,
ASE – enrichment value after starting the engine,
EGO – correction according to the lambda probe,
KS – enrichment at the moment of knocking,
IAT – correction as a function of the temperature in the suction manifold.

Control systems and algorithms known to authors use information from temperature sensors and fuel dose correction functions during engine start-up and heating, mainly to achieve smooth and stable operation and to obtain optimal exhaust composition. These solutions do not take into account the influence of oil temperature on engine wear, enabling the machine operator to immediately enter the operating state of the engine with maximum speed and load after starting. This condition is unfavorable, as the parameters of the engine oil lubricating oil are limited and the operating conditions are significantly energy-consuming. Therefore, the concept of an engine control system compatible with fuel dose correction in accordance with the "Alpha-N" algorithm and realizing the function of protecting the engine against intensive work in the event of insufficient oil heating was developed. The algorithm is presented in two options only with the engine temperature sensor (head) (Fig. 9a) and the engine temperature sensor in the head and the oil temperature sensor (Fig. 9b). A system without an oil temperature sensor requires tests to indicate the oil temperature and engine temperature during operation in different operating conditions (different ambient temperature) and the time of their achievement in order to develop the proper correction coefficients k_t and k_r. The system with the oil temperature sensor requires the use of a thermal switch that will change the signal sent to the speed control potentiometer, after reaching the set temperature, e.g. 80°C, enabling the adjustment of the rotational speed change. Adjustment of the system taking into account the temperature of the oil, taking into account only the temperature measurement of the engine, can be implemented by introducing, for example, two correction factors. The task of the first one is to indicate the oil temperature based on the engine temperature, and the second one is to adjust the inertia time of oil warming in relation to the engine head warming up:

$$T_s(r) = T_o(r \cdot k_t) + k_r \,, \tag{3}$$

where:
$T_s(r)$ – engine temperature as a function of sensor resistance,
$T_o(r)$ – oil temperature as a function of resistance,
k_t – the correction factor depends on the time of the engine oil temperature change relative to the temperature of the engine head,
k_r – correction factor depends on the change in resistance as a function of temperature.

The system equipped only with the engine temperature sensor (without the oil temperature sensor) shown in Figure 9a requires proper correction coefficients to be used in the calculation part. The work of the system starts with the detection of the engine temperature, the signal through the calculating component corrects the resistance value of the signal as a function of temperature using the coefficient k_r. Then, the correction k_t takes into account the randomness of temperature change at selected measurement points, it is dependent on environmental conditions, and mainly the air temperature, which in the modernized system is recorded by the sucked air temperature sensor , for calculating the composition of the fuel-air mixture. This signal can be used in parallel to the system in question. The processed resistive signal, the value of which represents the temperature of the oil is directed to the thermal switch, which after using the set value enables any speed control via a manual speed switch that acts on the servomechanism regulating the throttle valve opening angle. Optionally, in the system, a time switch can be added, which after starting the engine will limit the change of rotation speed parameters for a given time, allowing the engine to warm up without excessive wear.

Another method of control includes an oil temperature sensor in the system, which, combined with a thermal switch, prevents the change of rotational speed until the oil temperature corresponding to the hot engine is reached (Fig. 9b).

The operator cannot intervene in the regulation of the engine's heating process thanks to the electronically controlled air damper used in the developed engine [29]. This type of solution, which is not used in this group of engines, introduces wide development possibilities of these drive units with such systems as e.g. described in the article or adaptive and maintenance-free system and method of speed control of wood chipper drive [30].

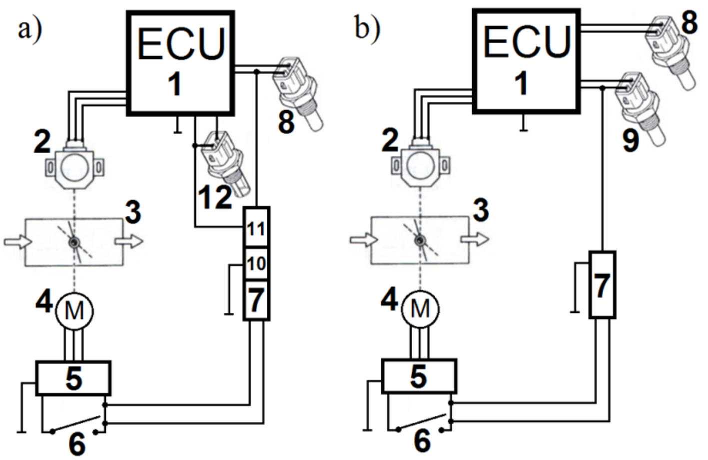

Fig. 9. Schematic diagram of the system protecting the engine from work with unheated oil at high engine revolutions, dedicated to the innovative injection-ignition system used in the German GX390 engine: a) only with the engine temperature sensor, b) with the engine and oil temperature sensor, where: 1 – electronic control unit, 2 – throttle position sensor (TPS), 3 – throttle valve, 4 – servomechanism, 5 – servo control, 6 – manual engine speed switch, 7 – thermal switch, 8 – engine temperature sensor, 9 – oil temperature sensor, 10 – time switch, 11 – calculation member, 12 – intake air temperature sensor

6 Conclusions

The research indicated that the temperature measurement of the engine in the head makes it possible to assess the change of oil temperature using the correction factors discussed in the paper. In addition, it can be observed that the oil warms up with a certain delay in relation to the engine head, it seems reasonable to apply a few minutes lock speed change in order to achieve optimal operating temperature of the oil. European legislators aim to reduce pollutants from all emission sources, including propulsion units designed for propulsion of non-road mobile machinery, subject to continuously updated approval standards for the emission of pollutants in exhaust gases. Such a situation will accelerate the introduction of electronically controlled injection-ignition systems in this type of mobile machines. It will enable their expansion to include other systems, such as those described in the paper, which by reducing operation in unfavorable working conditions will reduce the ecological hazard associated with accelerated consumption of these propulsion units through operation e.g. when working with an unheated engine. The introduction of solutions allowing the improvement of operating conditions and the use of the indicated machines is beneficial and most often requires interference in many areas of the problem. The development and application of an electronically regulated throttle tilt angle has made it possible to expand the control procedure, not only to regulate the air-fuel mixture, but also to regulate the speed of rotation according to the oil temperature described in the article, to reduce engine wear. The developed control ideas require extended research to determine the coefficients described in the text and to extend the prototype with the indicated control ideas.

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