MULTIDIMENSIONAL ENGINE STARTING CHARACTERISTICS

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Abstract

The difficulties in obtaining the start of piston combustion engines increase at low temperature conditions. Lowering abilities of a diesel engine to undertake the independent operating, at low temperature, result from its influence on exploitation materials, engine systems properties, and directly from lowering the temperature of sucked-up into the engine cylinders air. The successful engine start-up depends on three independent parameters: engine (and ambient) temperature, engine crankshaft rotational speed extorted by starting system and the time period at which this system is operating. An individual engine starting abilities measure can be the time of starter motor operating at a particular temperature or its start-up limit temperature determined according to a specified research standard. The dependence of start-up time or start-up limit temperature on any particular factor is the engine starting characteristic. The combustion engine is a very complex object in respect of its starting abilities. If the engine constructional, adjustment and exploitation parameters are changed, the start-up characteristic (function) is a multi-dimensional function. Formally, from mathematical point of view, it is a surface in a multidimensional space. It is possible to obtain any engine starting characteristic by multidimensional starting surface intersection. In the paper there are presented examples of one- and multi- dimensional diesel engine starting characteristics as results of long-lasting starting tests of many engines.

Keywords: *piston combustion engines, low temperature starting*

1. Introduction

The start-up of any technical device is process of its passing from its standstill to the state of useful tasks performing. Practically in every case the obtaining of any device independent operation is connected with supplying it with additional energy, independently of the fact whether this device consumes the energy or it is an energy source, strictly – transforms one form of energy to another. The piston combustion engine is a device designed to transform the chemical energy contained in an organic gaseous or liquid fuel into mechanical work. The engine start-up is especially important from its exploitation point of view – it begins the mechanical energy production. On the other hand the engine start-up, especially of diesel engine, at low values of ambient temperature forms an interesting research problem. Engine start-up at low temperature conditions is a separate area of piston combustion engine research. It results from a considerable increase of difficulties to put its in motion at low ambient temperature, negative in Celsius temperature scale. The problems of engine exploitation at low temperature conditions first of all result from the changes of constructional and exploitation materials properties. It especially refers to exploitation liquids. The basic problem is their considerably high viscosity, blocking of flow or even freezing.

The piston combustion engine starting properties, defined as the degree of its adaptation to undertake the independent operating at different ambient conditions, are important indexes of its usability features assessment. The measure of these properties is most frequently the engine limit starting temperature evaluated according to the requirements of the start test standards [1] or the engine start time at a particular temperature. There are known the dependences of start-up processes on many individual factors for the engines, both diesel and spark ignition, which are in the state of thermal equilibrium with its environment. As the temperature drops, the difficulties to obtain the engine independent work increase. It results from the temperature influence on two groups of factors deciding on possibilities of putting the engine in motion [3]. On the one hand the potential possibilities to crank the engine crankshaft with the help of the starting system drop. The engine resistance torque increases at lowered ambient temperature as a result of lubricating oil viscosity change. The suitable decrease of force moment (and the power) developed by starting system, most often electrical, is observed. It is caused by battery capacity decrease and its internal resistance increase, so the voltage on battery and starter terminals drops. The second area of adverse influence of low temperature on engine start-up processes concerns air-fuel mixture creating and its combustion conditions. In the case of diesel engine the thermodynamic parameters (temperature and pressure) of the compressed in cylinder air charge drop and the quality of fuel atomisation is worsened. The best way of technical device properties analysis and explaining is presenting its appropriate characteristics, which is the dependence of its any efficiency parameter on single or more independent factors. Similarly can be analysed and explained engine starting properties dependent on many its constructional, adjustment and exploitation factors.

2. Combustion engine basic starting characteristics

As it was stated above, the learning of features of technical object is connected with determination of its suitable sets of characteristics or parameters. It is evident that with regard to engine start-up properties the most complete description of these features would be a characteristic - defining these properties (limiting starting temperature of the engine) as a function of all factors determining them. It is also evident that its experimental determining, both in analytic and graphic form, is impossible. The required characteristics are possible to obtain, in general in experimental way, as functions of the only one independent parameter (factor) under condition of constant values of other quantities influencing the given utilizing feature of the device (starting properties – in this case). These dependences could be named as basic engine starting characteristics.

The piston combustion engine starting characteristics are determined during experimental research carried out according to the starting test standards in climatic chambers. The particular standard formulates some requirements on the methods of tests realization in different way, but general sense of individual method aspects remains stable. The most important condition of engine starting properties tests is to provide its thermal equilibrium with environment. Usually the time period of temperature stabilizing equals one day. The differences concerning the detailed conditions, especially in the aspect of engine and acid battery preparation and the way of start attempt can cause the difference in engine start-up properties evaluation. The range of engine start-up test principles determined by these standards can be divided into the following groups:

- determination of requirements concerning the test stand,
- determination of the tested engine state,
- the way of the engine preparation for the start attempt,
- the way of engine starting attempt carrying out,
- the principles of analysis and evaluating of starting test result.

To start any device, as it was pointed above, to initiate working processes, it is necessary to supply the external energy. In the case of piston combustion engine the only way of this energy supplying is the engine crankshaft cranking with the help of the starting system. If during the energy supplying process the engine or another device does not begin to operate independently, we can talk about unsuccessful start-up, in the opposite case – successful start-up. So the engine starting can lead to one of these two results – the states of engine operating.

The basic and most often determined engine start-up characteristic is the dependence $t_s(T)$ of its start time t_s on the temperature value T. Additional parameter of engine start properties evaluation can be the first ignition time occurring t_i, because it contains the information on the course of individual engine starting phases. An example of such dependences for AD4.236 engine is given in Fig. 1. If at a given temperature the starter motor operating time is equal to maximum value specified according to the test standard, then this temperature value is the limiting start temperature of an engine.

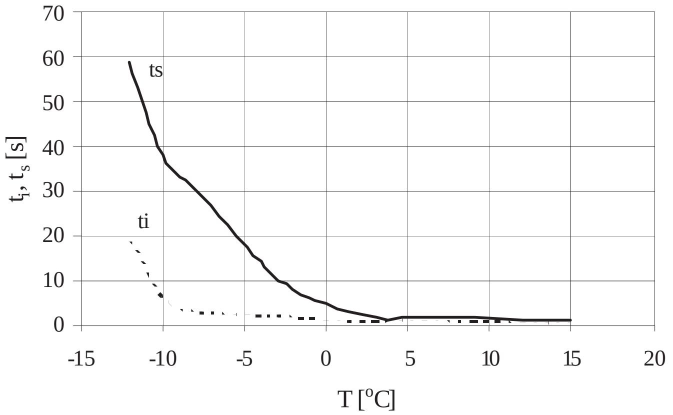

Fig. 1. The course of the basic engine start characteristic t(T) for AD4.236 engine

It is necessary to notice that the course of the curves obtained in such way, during the experimental tests, is also the consequence of the fact that in the case of crankshaft extortion by a starter system, e.g. electric, there is not fulfilled the assumption that the mean value of crankshaft rotational speed is steady at different ambient temperatures. The crankshaft rotational speed is changing due to the change of oil viscosity and acid battery capacity. Because of it the driven crankshaft rotational speed often is treated as an independent factor extorting starting processes in engine cylinders. The independent change of the rotational speed could be received by using different oils or batteries at different capacity.

So an extraordinary important start-up characteristic of the piston combustion engine is the *n*(*T*) dependence or reverse dependence *T*(*n*), which ensure the constant engine start time. And if in that case the *t* value would be equal to the one admissible by the start tests standard, it would be obtained the dependence of minimum engine start rotational speed on the temperature, or in the second case – the dependence of engine limiting starting temperature (according to the standard) on crankshaft rotational speed extorted by the starter motor. Such characteristic for the AD4.236 engine was obtained using a computational model for thermodynamic parameters of the engine cylinder charge during engine starting and presented in Fig. 2. [3]. Parameters (*T*, *n*) of some points of this characteristic were verified experimentally.

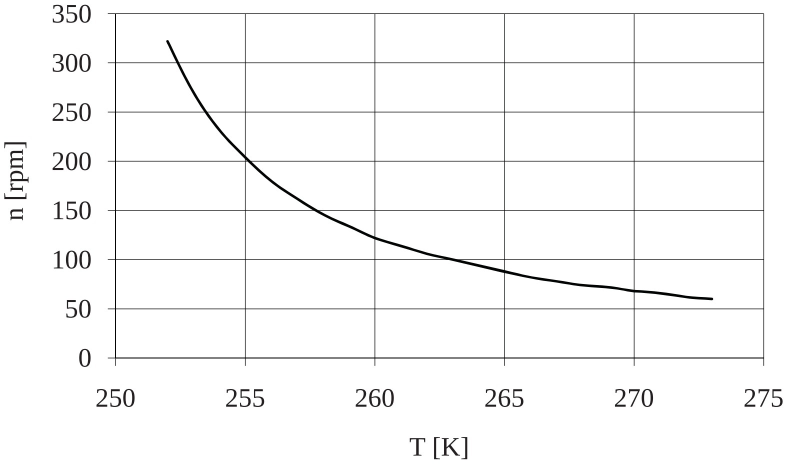

Fig. 2. The dependence of the AD4.236 engine minimum starting rotational speed on temperature

A significant aspect of the combustion piston engine research is finding its start-up adjustment characteristics, which determine the dependence of its starting properties on its constructional, adjusting or exploitation parameters. The example of the adjusting start characteristic received during the experimental tests of AD4.236 engine – the dependence of its start time on the fuel injection timing φ at the ambient temperature of -12^{o}C (261 K) is presented in Fig. 3 [3].

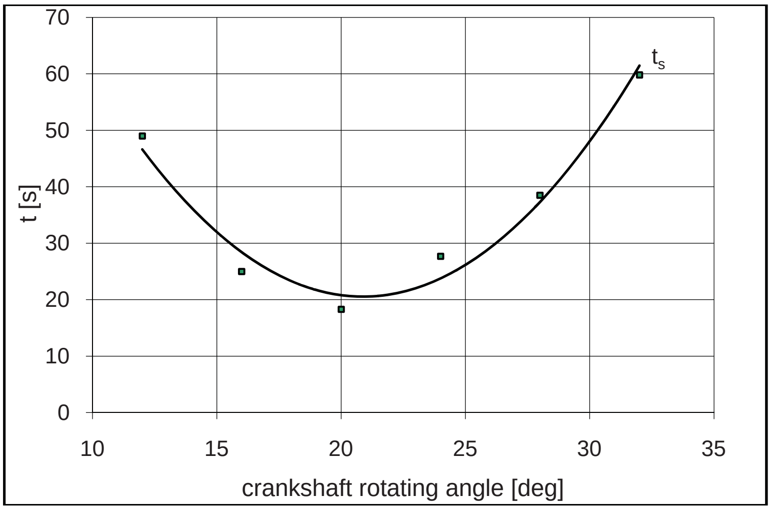

Fig. 3. The dependence of the AD4.236 engine start time t_s on the fuel injection timing at the temperature of –12°C

The primary goal of the adjustment characteristic research is the optimization of the engine start properties. A macroscopic parameter of these parameters influence evaluation on engine start can be the value of the obtained limiting start temperature or engine start time at a constant ambient temperature. In many respects taking into account the engine start time is more advantageous, first of all because of the research labour consumption and their expense. Especially in the case of adjusting characteristics one is aiming at obtaining of the dependence in analytic form using approximation of them with polynomial functions – most often the second degree. These are so called research object functions [2], and for the dependence presented in Fig. 3 its function form obtained using the least squares method expresses the equation:

$$t = 0{,}331\varphi^2 - 13{,}82\varphi + 164{,}9 \ \text{[s]}. \tag{1}$$

Analytic description of these characteristics let us in easy way determine the optimal value of the factor, which ensure the minimum engine start time.

3. Multidimensional engine starting characteristics

The engine starting can be successful or not, if the engine does not start operating after the starting process. To start the engine it is necessary to drive its crankshaft with a certain rotational speed. It is known that its indispensable value, for a successful start-up, increases as the ambient and engine temperature drops. For suitable combination of the temperature and crankshaft rotational speed values the engine start-up can be obtained after some time of starting device operation – engine crankshaft turning. The engine start time increases as the temperature and engine crankshaft rotational speed drop. So, the independent work of piston combustion engine obtaining is dependent on the values of three independent parameters:

- the engine and its ambient temperature – T,
- engine crankshaft rotational speed extorted by a starter motor – n,
- the engine starting system operation time – t.

These three parameters have closely connected values. To a given combination the two of them corresponds the only one value of the third parameter. Because of it is possible to obtain in three dimensions space a starting characteristic of an engine. In Fig. 4 it is presented the dependence of the AD4.236 engine start time *t* on the temperature *T* and crankshaft speed *n* values. It is three-dimensional engine starting characteristic. The drawn in three-dimensional coordinates system (*T*, *n*, *t*) limiting surface separates the two areas: area of unsuccessful and successful start-ups.

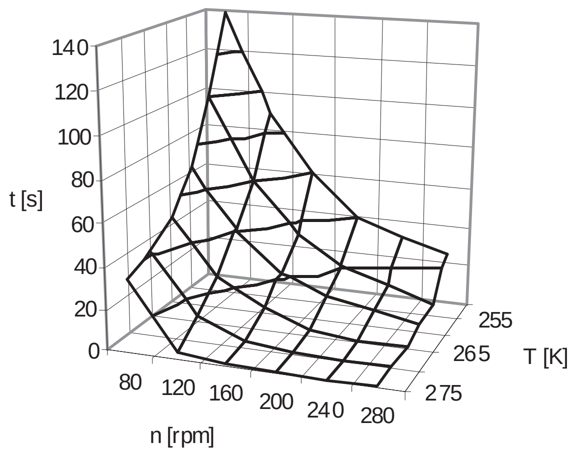

Fig. 4. The dependence of the AD4.236 engine start time t on the temperature and crankshaft speed values

It is evident that the basic (two-dimensional) engine starting characteristic could be obtained on the base of multidimensional characteristic. For example, the basic starting characteristic of the engine *t*(*T*) can be obtained by intersection of limiting surface in Fig. 4 with *n* = const surface (cutting plane) and the characteristic *n*(*T*) – by intersection with *t* = const surface.

The effective parameters and work characteristics of the engine depend on its constructional features, adjustment parameters and exploitation factors. That is why there are determined the dependences of the engine torque on these parameters values, named as its adjustment characteristics. Similar dependencies can be determined for the combustion engine in relation to its start-up properties. Therefore there is a possibility to define and determine multidimensional engine starting characteristic by changeable values of its constructional, adjustment and exploitation features. Such characteristic was made on the base of obtained starting tests results of several diesel engines with direct fuel injection. It can be treated as an experimental model of such diesels starting.

The base for creating both physical and mathematical models of the engine starting processes is the analysis of air-fuel mixture creating and self-ignition. Considered diesel engines with direct fuel injection are characterized by similarity of combustion chamber (toroidal chamber located in piston). Because of it the main factors determining compressed in engine cylinder air thermodynamic parameters (temperature, pressure) are: real degree of air charge volume change and crankshaft rotational speed. On the rotational speed value are also dependent features of the sprayed stream fuel. From among the parameters characterising supplying with fuel process there was taken into account in the model only injector opening pressure. It was because the fuel dose in its volume equal or more than engine nominal dose, which is applied during the engine starting, influences in a slight degree on engine starting properties. Therefore in considered model – diesel engines starting characteristic there were taken into account three independent factors determining starting properties of diesels with direct fuel injection:

- crankshaft rotational speed extorted by starter – *n* [rpm],
- real degree of cylinder air charge to the fuel injection beginning – ε_r,
- injector opening pressure – *p* [MPa].

The values of factors mentioned above, determining starting properties of considered engines, ordered according the criterion of growing the limiting starting temperature, are put in the Tab. 1.

Tab. 1. The set of parameters determining the limiting starting temperature of considered engines

Lp.	engine	T [°C]	*n* [rpm]	ε_r	*p* [MPa]
1.	AD3.152UR	-15	121	10.8	17.2
2.	Z 8401.12	-14	155	8.1	16.8
3.	SW 680	-14	178	6.8	17.0
4.	3X6AaP (17)	-13	165	8.9	19.8
5.	Z 8002.1	-12	110	8.1	16.6
6.	T4 391S	-12	240	8.2	24.5
7.	Z 8401.1	-12	113	8.1	16.8
8.	H6AaC-HX (17)	-12	160	9.2	19.8
9.	A4.236	-9	106	8.4	16.8
10.	6 CT 107	-5	180	7.0	19.8
11.	H6AaC-HX (36)	-2	206	4.9	19.8
12.	3X6AaP (36)	0	180	4.8	19.8

Notice: numbers (17) and (36) for the 3X6AaP and H6AaC-HX engines mean the angle of fuel injection advance

The other factors determining of this engine set starting properties were accepted as constant. As it was mentioned above all the engines are diesels with fuel direct injection into located in piston combustion chamber. Moreover it concerns first of all diesel fuel properties and engines starting method. All the engines were started according to BN-74/1345-09 standard requirements.
The analysis of the set in Tab. 1 data indicates, that there is no one of independent factor of the model which determines individually the engine starting properties level. So all parameters are important for elaborated model, but the most significant influence on engine starting properties diversifying have undoubtedly the real degree of air charge volume change ε_r.

The model of the dependence between dependent variable and independent factors may be obtained using regression method analysis. The accuracy of the determined model is evaluated with the help of statistical parameters. As the basic parameters of this assessment were adopted correlation coefficient and standard deviation. The calculating of the regression expression was implemented with the help of the smallest squares sum method using computer software. Making an assumption that the regression function should be mathematically the simplest and simultaneously should ensure high accuracy, there were taken into consideration the linear, power and hyperbolic expressions. Applying exclusion of the least essential elements with the help of Fisher's test, there was obtained the most accurate expressions:

- for the linear function:

$$T = -0.1037n - 3.169\varepsilon_r + 1.731p - 1.3 \ [^{o}C], \tag{2}$$

- for the second step polynomial function (with the combination of the three factors):

$$T = 0.2903n + 13.744\varepsilon_r - 0.508\varepsilon_r^2 + 0.1744p^2 - 0.002865n\varepsilon_r p - 126.8 \ [^{o}C], \tag{3}$$

- for the functin in which existed the second step power and hyperbolic components:

$$T = \frac{12848}{n} + 0.5830p^2 + 0.28049n\varepsilon_r - 0.6169\varepsilon_r p - 0.011585n\varepsilon_r p - 284.8 \ [^{o}C]. \tag{4}$$

The most accurate results for the calculated limiting starting temperature of the engines were obtained in the case of function (4) including power and hyperbolic components. In this case, the squared correlation coefficient value $r^2 = 0.98$ and standard deviation value $SE = 0.87$ °C. In Fig. 5 there are presented the values of differences of limiting engines starting temperatures obtained experimentally and with the help of expression (4).

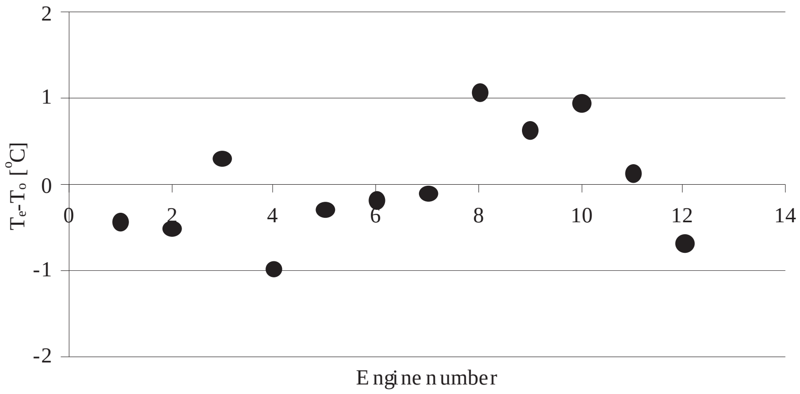

Fig. 5. The differences of limiting starting temperatures of the engines determined experimentally – T_e and calculated using expression (4) – T_o (Engine number is compatible with Tab. 1)

The obtained in the case of expression (4) the degree of compatibility of calculated and experimentally determined engines limiting starting temperature can be acknowledged, on the base of statistical parameters, as very good. In the ranges of independent factors change:

- crankshaft rotational speed extorted by starter: n – 100-250 rpm,
- the real change of compressed in cylinder air charge volume: ε_r – 5-11,
- the pressure of fuel injector opening: p – 17-24 MPa.

the diesel engines with fuel direct injection limiting starting temperature can be calculated with the help of expression (4) ensuring enough great accuracy. The obtained degree of compatibility of calculated and experimentally determined engines limiting starting temperature constitutes also confirmation of made assumptions rightness that the fundamental, determining starting properties of these diesel engines factors are: crankshaft rotational speed extorted by starter, the real change of compressed in cylinder air charge volume, the fuel injector opening pressure.

The determined expressions (2, 3, 4) are appropriate multidimensional starting characteristics of diesel engines. They determine different dependences of diesel engine with fuel direct injection limiting starting temperatures (according to BN-74/1309 standard) on the three different parameters (in fact, the real change of compressed in cylinder air charge volume includes three other factors: compression ratio, angle of fuel injection advance and angle of inlet valve closing). Of course such dependence could not be presented in graphical form. In three-dimensional space it is possible to draw a surface corresponding to determined characteristic if one on the factor will be treated as a parameter and will have a constant value. In Fig. 6 there is shown a surface illustrating the change of DI diesel engine limiting starting temperature according to expression (4) by a constant value of the fuel injector opening pressure p = const = 20 MPa and depending on crankshaft rotational speed extorted by starter and the real change of compressed in cylinder air charge volume.

It is evident that assumption of p = const = 20 MPa in actual fact means intersection of determined characteristic of limiting starting temperature by the plane p = 20 MPa. So, as it was stated above, also in case of this multidimensional starting characteristic we can obtain more simple characteristics by intersection it by any plane or surface.

The obtained in Fig. 6 surface shape illustrating the characteristic quite distinctly reflect the known dependences of diesel engine properties (limiting starting temperature) on individual factors. The engine limiting starting temperature depends on the real change of compressed in cylinder air charge volume quite linearly and its gradient has higher value at lower value of crankshaft rotational speed. The dependence of limiting starting temperature on extorted by starter crankshaft rotational speed has non-linear character, but similarly its gradient has higher values at lower values of the real change of compressed in cylinder air charge volume. These are the new observations of the dependences on the base of obtained multidimensional starting characteristic.

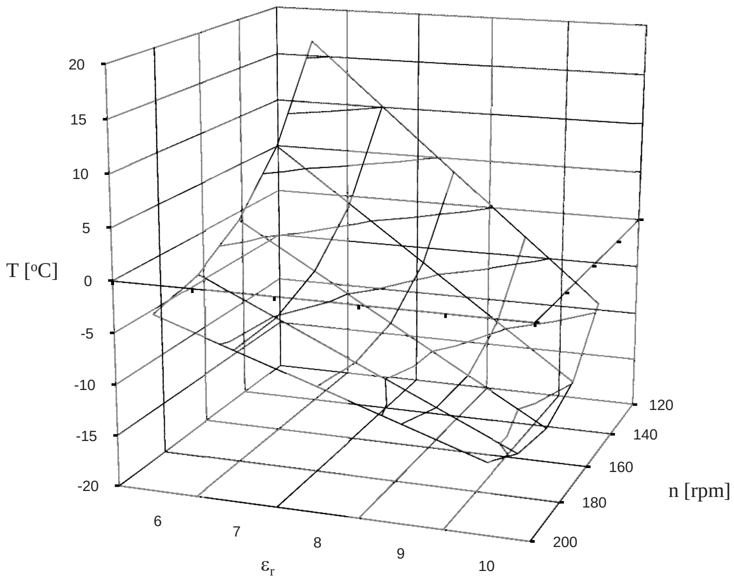

Fig. 6. The dependence of diesel engi ne limiting starting temperature determined according to expression (4) by constant value of p = const = 20 MPa

4. Closing remarks

The piston combustion engines starting properties depend in complex way on many parameters characterizing both the external extortions for start-up processes course (temperature, the rotational speed of crankshaft, the engine start system operating time) and the different engine features, its systems and exploitation materials characteristics. The engine starting characteristic should be considered in mathematical sense a multidimensional function of engine constructional, adjusting and exploitation features. The simple, basic, generally one-dimensional starting characteristic can be treated as a suitable intersection of the multidimensional characteristic with the k–1 dimensional surface, where k is the number of the independent parameters influencing the piston engines starting properties.

The aim of engine starting properties research most often is to obtain its basic, one-dimensional characteristic. These dependences let simply clear up the influence of a single factor on the engine starting processes. The receiving of a multidimensional engine starting characteristic is first of all a long-lasting and costly research process. These type characteristics, especially expressed in mathematical form, show the complexity of engine starting dependencies and mutual influence of particular factors on engine starting properties.

References

[1] Mysłowski, J., *Rozruch silników samochodowych z zap łonem samoczynnym*, WNT, Warszawa 1996.
[2] Polański, Z., *Planowanie doświadczeń w technice*, WNT, Warszawa 1984.
[3] Pszczółkowski, J., *Charakterystyki rozruchowe silników o zap łonie samoczynnym,* Stowarzyszenie Edukacyjne Pedagogów Praktyków Cogito, Zbąszynek 2004.