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IGNITION SYSTEM AND THEIR PURPOSE IN AIRCRAFT RECIPROCATING ENGINES

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Abstract

This research describes the function and principles of ignition systems in aircraft reciprocating engines. Physical-chemical processes, which are part of combustion, and the factors affecting them are defined in detail. Types of ignition systems are divided based on main parts and frequency of appearance in aircraft engines. Components of ignition and their function in electric and magnetic circuits are individually described. The future development in ignition systems is defined. The research includes an analysis of the pros and cons of laser ignition in its application in aviation. It presents Low-Temperature Combustion or Volumetric Ignition using Low-Temperature Plasma. An example may be the Microwave-assisted Plasma Ignition System. Engine speed and vacuum in intake are the main parameters influencing the ignition timing curve in Electronic Control Unit Master developed by IMF Soft. This ECU is used in the designed ignition system of testing engine. The designed timing curves were tested, and the results of engine power and torque were compared. In conclusion, the optimal timing curve is evaluated for this reciprocating engine.

Keywords

Ignition system. Ignition. Spark Plug. Aircraft reciprocating engine. Laser. Low Temperature Combustion

1. INTRODUCTION

The purpose of the ignition system is to ignite the mixture of fuel and air in the cylinder. An electric spark is used for ignition, which is created between two electrodes of an electric spark plug as a result of a high-voltage discharge. We can obtain electrical energy from several sources. The main ones are accumulators and magnetos. Electric current flows from the battery to the primary winding of the coil, thereby inducing a magnetic flux in the core of the coil. If the flux is interrupted, a high voltage is induced in the secondary winding. That is proportional to the rate of change of the magnetic flux and the number of turns. [1]

1.1. Breakdown voltage

By ionizing the gas between the electrodes of the spark plug, a conductive path is created for the transfer of electrical energy, which passes from one electrode to another in the form of a discharge. A voltage that is higher than the electrical resistance of the gas is named a breakdown voltage.

If the spark jumps but does not have enough energy, the mixture will not ignite. Therefore, instead of the energy of 0.1 MJ, which is enough to initiate the spark, the energy of 50 to 120 MJ is required. Because of the highly ionized gas, it is also necessary to increase the voltage on the electrodes; it varies between 10 and 30 kV. [1]

Conditions for proper ionization may vary. If they are positive, the breakdown voltage value is lower and if negative, the breakdown voltage will be higher. Factors affecting the breakdown voltage include pressure inside the working space, the distance between electrodes, temperature, the composition of the mixture, and humidity or material of the electrodes. [2] [3] [4]

1.2. Combustion process

Combustion is a physicochemical redox exothermic oxidation reaction in which a combustible substance reacts quickly with an oxidizing agent to produce heat and light. For a combustion reaction to occur, three conditions must be met: the presence of a combustible substance (fuel), the presence of an oxidizing agent (oxygen), and the source of initiation, which in this case is represented by an electric spark. [5]

Combustion processes are associated with the transfer of substances through heat sharing under high-temperature gradients, while the transfer phenomena tend to be accelerated by turbulence, which overlaps the molecular transfer, which is abided by the kinetic theory of gases. [6]

The burning of the fuel mixture inside the working cylinder of the engine can be characterized as a flame of a spherical surface spreading from the point of ignition, the gradual speed of which increases with pressure and temperature and swirling of the cylinder. It also depends on the composition of the mixture and the ratio of combustible components to inert gases. [7] It can be divided into several stages, which, however, may overlap or take place in parallel in different parts of the combustion chamber. [6] For simplicity, the combustion process is split into two phases, where the first part of the combustion is referred to as the inductive phase and the second part as the visible combustion phase. [1] [2]

2. LASER IGNITION

Using a laser instead of a spark plug brings many significant advantages. One of the most important is the possibility of igniting the mixture anywhere in the cylinder, by focusing the lens, i.e. aiming the ray. This results in lower energy losses, which, among other things, are derived from the cooling of the mixture from the walls of the cylinder. By using multiple sources of separate laser beams (especially two- to three-beam units), create multiple ignition points (shown in Fig. 1). Thanks to this, the burning process is more uniform and the flame is more homogeneous. The reduction of losses and increase in efficiency will be achieved. [8] [9]

igniting the mixture with a spark plug takes a few milliseconds. By using a laser, it is possible to speed up this process, and therefore the time interval for ignition of the mixture is in the order of nanoseconds, and the timing can be made even more precise. The ability to ignite a leaner mixture at a lower temperature and higher compression ratio makes laser ignition a much more efficient system than the older one. It contributes to lower fuel consumption and decreases CO2 and NOX emissions. [8] [9]

There are four types of laser ignition: non-resonant ignition, resonant ignition, thermal ignition, and photochemical ignition. The most promising type, which is also the most similar to conventional ignition with a spark plug, is non-resonant laser ignition.

Currently, the use of laser in the ignition is only at the theoretical and experimental levels. That is mainly due to the size of the entire mechanism and the very high energy emitted. The energy density in the ignition focus reaches 100 GW.cm-2 and the pulse energy is 10 to 100 mJ during 10 ns. Laser ignition should bring advantages mainly to multi-cylinder piston engines using a multiplex system (multipoint ignition), which sends pulses from a single laser to each cylinder through optical fibers. The problem is the rapid wear of optical fibers. The solution could be to split the laser module into multiple micro-laser units (the size of a spark plug) and then install them into the engine cylinders. These units would be connected to the energy source using the mentioned optical fibers, but with lower light intensity. [8]

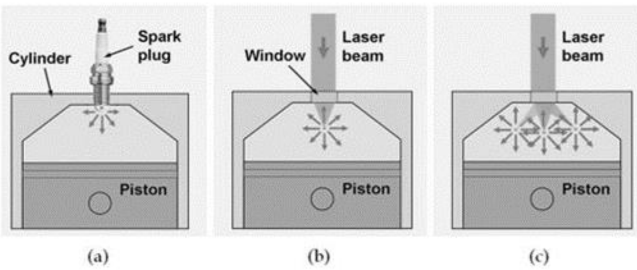

Figure 1 - Types of ignition. (a) spark plug ignition, (b) laser igition, (c) multipoint laser ignition

3. LOW-TEMPERATURE PLASMA COMBUSTION

In the use of low-temperature plasma, in contrast to the use of high-temperature plasma, heat loss and heat load of the ignition system are not a problem, because the highly excited particles are only electrons, not ions and neutrons. Chemical reactions can be enhanced by more efficient energy transfer between electrons and reactants. Today, the price of such a system is incomparable to classic ignition systems (TCI – transistorized coil ignition). However, at the same time, it shows a high potential for increasing combustion efficiency. Compared to laser ignition, it offers lower costs and higher efficiency, and there is no need to run optical cables to the engine. [10] [11]

Many kinds of research deal with low-temperature combustion (LTC) ignition systems such as "streamer discharge", "surface ignition", "nanosecond pulsed dielectric barrier discharge" and "high-frequency resonance plasma ignition". As it turned out, the use of low-temperature plasma in a real engine is inconvenient mainly because of maintaining a stable low-temperature plasma under high pressure. [10]

3.1. MAPIS

Due to the shortcomings, it is better to use a hybrid of low-temperature plasma and convection ignition. One of the projects is a Microwave-assisted Plasma Ignition System. [10]

Ignition is initiated by conventional ignition, which is subsequently extended by the emission of microwave radiation into the discharge area. The application of the MAPIS system successfully achieved a reduction in the amount of fuel in the mixture (leaner mixture), fuel consumption, and emission characteristics compared to convection ignition systems. [10]

Low-temperature plasma is known to have a higher electron temperature and is more active due to the rapid production of radicals (electron groups) and excited species by electron collision dissociation, excitation, and subsequent energy "relaxation". For the MAPIS system, the electron temperature increase and the electric field decrease are lower than in other low-temperature plasma systems. These are radio frequency systems or systems using nanosecond pulses. Compared to these systems, it has a more stable discharge that ensures convection ignition under all conditions. [10]

MAPIS is formed of four main parts: power source, transmission system, power monitoring system, and igniter. The energy source is a magnetron and an ignition coil. A magnetron is a generator of microwave electromagnetic radiation. In this particular case, a radiation frequency of 2.45 GHz needs to be achieved. [10]

In Fig. 2 the four phases of MAPIS ignition are shown. First, it is necessary to create an intense microwave field (I). Since the energy contained in microwave radiation is less than the minimum ignition energy, the spark plug is used first; it will form a small source of plasma (II). This plasma source absorbs microwave radiation and expands; radicals are formed, and microwaves improve combustion (III). During IV. phase final flame propagation in the engine cylinder occurs. [11]

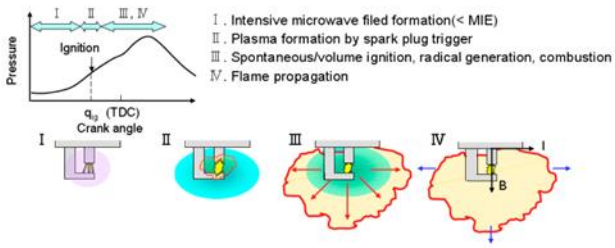

Figure 2 - Phases of MAPIS ignition

4. LOW-TEMPERATURE COMBUSTION

The trend in ignition systems and general in the process of ignition and combustion of the mixture is to reduce the temperature. Such systems are called Low-temperature Combustion (LTC). The temperature is reduced by greater use of exhaust gas recirculation (EGR) and with an excess of air greater than 1 ($\lambda > 1$). Under stoichiometric mixture conditions, the fuel oxidizes with air at a higher temperature, which results in more NOX and soot emissions. To overcome evaporation and ensure proper atomization of the mixture a higher injection pressure of the mixture is used. To achieve proper atomization of the mixture, it is necessary to extend the ignition delay; different methods are used – reducing the compression ratio, higher use of exhaust gas recirculation, or variable valve timing. Usage of these methods in real conditions, while maintaining or even increasing the thermal efficiency of an engine, is a difficult task. Using Low-temperature Combustion is possible to achieve a decrease in NOX and other emissions by more than 80%. [12]

Low-temperature combustion has multiple models such as PPLTC (Partially Premixed LTC), HCCI (Homogenous Charge Compression Ignition Combustion), PCCI (Premixed Charge Compression Ignition Combustion), RCCI (Reactivity Controlled Compression Ignition), HECC (High-efficiency Clean Combustion) and SCCI (Stratified Charge Compression Ignition). Disadvantages of this combustion are imperfect combustion of HC emissions, lower operating range, unstable ignition control, transient response, and cycle-to-cycle variation. LTC is divided into three phases - pre-combustion, ignition, and post-combustion. The first phase depends on electric current and the change in its current; the middle phase is affected by the rate of a chemical reaction and the last phase depends mainly on the grade of mixing the mixture. [12]

4.1. HCCI

Homogeneous Charge Compression Ignition. Another name for the same principle could be "Controlled Auto-ignition Combustion". [12]

This type of ignition brings benefits from both gasoline and diesel engines that complement each other and improve the overall process. The advantage of this system is not only the reduction of NOX and soot emissions but also a much higher thermal efficiency reached for HCCI engines, which exceeds the value of 50%. It is also achieved thanks to the perfect mixing of the mixture before ignition; it can be mixed inside the cylinder, or in the space of the intake channel above the valve. As a rule, a leaner mixture is used, which produces flue gas at a lower temperature. Experiments have shown that the limit ratio of excess air at high pressure is λ=2.9 (conventional ignition has a limit of around λ=1.7). The maximum measured ratio during stable engine operation is λ=6.2. That was achieved at a very high pressure and temperature supply. [12] [13] [14]

This method is therefore based on compressing a homogeneous mixture of fuel, air, and minor gases to a temperature corresponding to the auto-ignition temperature. The main advantage over ignition with a single spark plug is the ignition of the mixture in different places in the cylinder at the exact moment, without significant flame spread. Knocking may occur due to unpredictable auto-ignition and high-frequency oscillation due to high pressure. [13]

Great emphasis is put on controlling the moment of ignition of the mixture (self-ignition), which is affected by several factors that change with engine speed and load. Compared to standard ignition systems, where the ignition advance is mainly regulated, in this case, it is necessary to change a wide range of parameters, such as the composition of the mixture, temperature, pressure in the cylinder, etc. To prevent early ignition of the mixture, a change in the compression ratio, the richness of the mixture, or the number of recirculated gases (EGR). If the ratio of recirculated gases to intake air increases, the specific heat capacity of the cylinder increases; the temperature rise in the cylinder is much lower and the mixture ignites much later. If the ignition timing of the mixture is optimized by reducing the compression ratio, the heat of compression will be reduced, and the ignition will also occur later (closer to the top dead center). [15]

5. RESEARCH

5.1. Systems installation

The practical part of the research aims to prepare the Rotax 915 iS engine (Fig. 3) so that it can be connected to the ECU Master control unit from IMF Soft. The way the research is being held can be called reverse engineering. In the next phase, the ignition system is tested concerning the performance parameters of the engine.

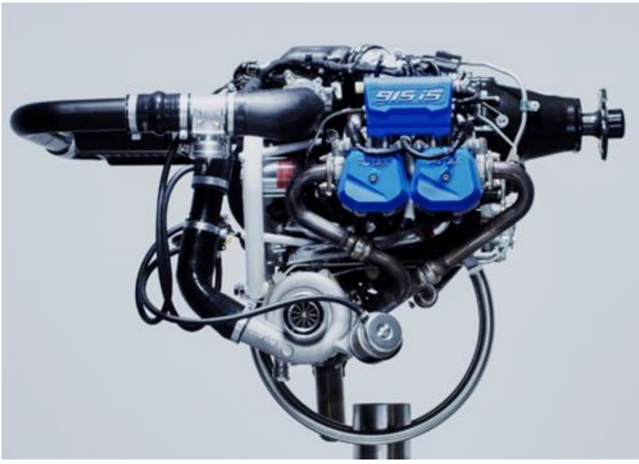

Figure 3 - Rotax 915 iS [16]

Our Rotax 915 iS engine was not equipped with fuel, oil, ignition, starting systems, and a control unit. Therefore, it was necessary to install the missing components on the motor. The fuel system consists of a tank from which fuel flows to the first pair of cylinders, then through an internal pipe and the remaining two cylinders. From them, a waste branch for unconsumed fuel leads to the second tank. The engine is fitted with eight injection ports, but for our purpose, we use only four (the other four are backups) - each for one cylinder. The control unit is equipped with two injection control outputs, and therefore fuel is injected into each cylinder twice in one cycle. The first injection is applied at the end of the expansion stroke, and the second during the exhaust stroke. The second application of fuel helps to cool the walls of the working cylinder; therefore, the engine can run properly.

The starting system consists of a power source, an electric starter, a switch, an electromagnetic relay, and wiring. The negative pole is grounded to the engine block, and the positive is connected to the relay (Fig. 4). The control signal from the switch on the control panel (small connector on the right side) and the negative pole (small connector in the middle) are connected to the relay, which electrically operated switch. When the switch is turned on, the contacts inside the relay are closed, and the 12 V current flows through the connector, which is found on top of the relay marked in yellow-green color, to the electric starter, which rotates the engine.

Figure 4 - Starting relay

The ignition system consists of an electrical power source, electromagnetic coils (TCI), a spark plug, and low and high-voltage wiring. The mechanical circuit breaker and distributor are replaced by an electronic control unit. The scheme according to which the components of the system are connected to the control unit is shown in Fig. 38. The wiring is connected to the control unit using FASTON connectors with a sealing rubber grommet. For crimping, we used standard FASTON crimping pliers 1.5-2.5 mm. And we put appropriate rubber seals in unused TYCO connectors to maintain IP65 protection.

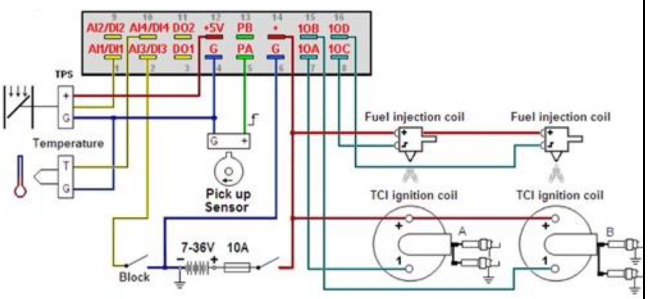

Figure 5 - Schematic of ignition system

The connection of coils had to be distinguished and connected. The outputs from 10A and 10B are provided to the negative contacts of the ignition coils. The signals from these outputs control the induction of high voltage, which is conducted by high-voltage cables to the spark plugs. From the positive output (14) an electric current is led to both coils. Because two spark plugs are connected to one induction coil, a spark is created in each cylinder twice in one cycle. First in the compression stroke, and the second spark is created in the exhaust stroke. Thanks to this, only two control signals from the control unit can be used.

The spark plug used in the test engine is a 297656 series manufactured by Rotax and is a dual-electrode type. Under normal circumstances, the engine has eight spark plugs, so there are two separate spark plugs in each cylinder, which are connected to different ignition coils. Such a solution is used in aviation mainly for backup purposes in the event of a single spark plug or coil failure, but also for better combustion of the mixture. However, in our case, we fitted the engine with only four spark plugs, i.e., there is only one in each cylinder.

5.2. Engine control

After successfully equipping the engine with all the necessary systems, it was necessary to set the control unit for starting and correct operation of the engine. Since we were working with a control unit with undefined functions of the engine manufacturer, it was necessary to figure out most of them by the experimental method.

As already mentioned, the first thing to do was to set the Pickup crankshaft position sensor. The scanned disc consists of 34 teeth and a gap that represents 2 teeth, so we used the setting defined as 36-2. Each tooth corresponds to a size of 10°, where it is also necessary to enter the beginning and end of the tooth in degrees (Fig. 6). By measuring, we found that the angular value of the disk, when the first cylinder is at top dead center, is 90°, but on the opposite side of the direction of rotation of the crankshaft. Therefore, we set the PA offset value to -90. This is therefore a shifted beginning of the cycle.

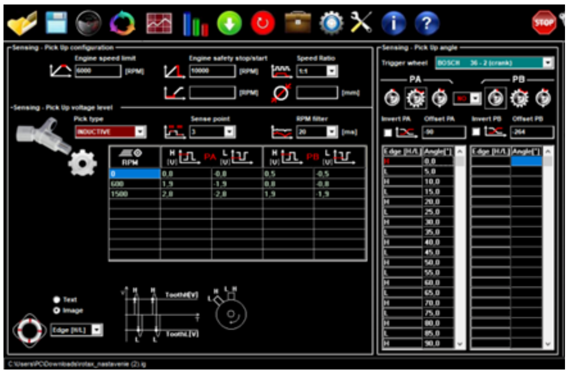

Figure 6 - Configuration of position sensor

Fig. 7 shows the ignition advance curve used, and its final one was created based on tests while the engine was running. Its minimum advance value is 9° at zero revolutions. It increases logarithmically up to 3500 revolutions per minute and subsequently flattens out and increases linearly up to a value of 40° at 6000 revolutions per minute, which represents the maximum engine revolutions. In our conditions at 17 °C, i.e. a standard air density of 1.1567 kg.m-3, the engine reached a maximum of approx. 3500 rpm. In the entire range of revolutions, the engine was running adequately for its condition and without major signs of detonation.

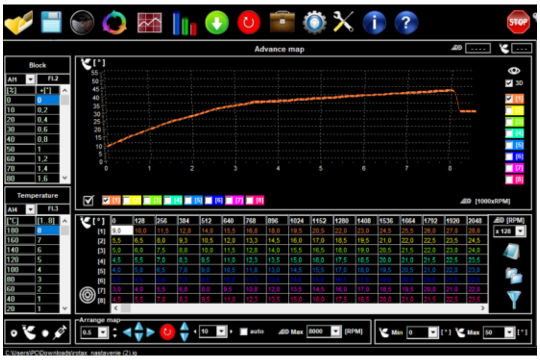

Figure 7 - Ignition curve

Setting the injection time of the fuel and air mixture into the cylinder spaces is done in the "injection map" tab, and the curve used can be seen in Fig. 8. Its modeling was also created while the engine was running, and its final version is reflected in the smoothest and cleanest running of the engine. The basic time of open injection is 0.6 ms at zero engine speed, its initial phase is flatter and only at about 800 rpm, when the timing is set to 1.3 ms, there is a steeper growth. This phase ends at approx. 2400 rpm, when the injection timing is 4.5 ms. The curve subsequently has a more gradual linear growth and the maximum injection opening value is 6.3 ms at 6000 rpm.

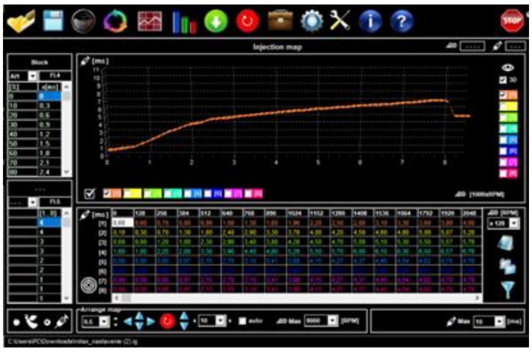

Figure 8 - Fuel injection map

6. CONCLUSION

The aim of the research was to put into operation the exhibition engine Rotax 915 iS, which was without any functional systems. In the first phase, it was, therefore, necessary to determine the condition of the engine and propose a solution for the individual systems. Among them were cooling, oil, fuel, starting and ignition systems, or intake systems. After installing the systems, the question of starting and controlling the engine arose. The ECU Master control unit from the manufacturer IMF Soft was used to operate the engine on the software side. Since the engine manufacturer does not supply any operating software for third-party control units, it was necessary for us to find the correct settings ourselves. Such a process can be named reverse engineering, where one proceeds in the opposite direction; a way to adapt the engine to the control unit was sought. And due to the lack of documentation, it was necessary to find the settings experimentally. The first task before actual commissioning was to define the offset of the induction sensor control wheel. Subsequently, the ignition advance curve and the fuel injection map were modified. After the successful start of the engine, it was necessary to further modify both curves to achieve the correct operation of the engine without detonations. The goal, which included mounting the engine and starting it, was achieved. The indisputable advantage of the research is the possibility of further scientific and practical research on the given engine, which will undoubtedly follow.

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