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SELECTED CHARACTERISTICS OF THE ELECTRIC PROPULSION SYSTEM OF AIRCRAFT AS FOUND OUT FROM THE GROUND-BASED LABORATORY TESTS

Zbigniew Jakielaszek, Mirosław Nowakowski

Air Force Institute of Technology
Ksiecia Boleslawa Street 6, 01-494 Warsaw, Poland
tel.: +48226852005, fax: fax +48 22 8364471
e-mail: zbigniew.jakielaszek@AFIT.pl, miroslaw.nowakowski@AFIT.pl

Abstract

The paper is a discussion on ground-based laboratory tests of the aircraft's electric propulsion system. The tests were intended to find relationships between environmental conditions and characteristics of the aircraft electric motor. The object under examination was a brushless DC motor AXI 2820/14 of 360 W power. Presented and discussed is the AFIT-made test bench that enables suitable, pre-planned experiments to be carried out. Discussed are also procedures of taking measurements of electric motor characteristics, followed with discussion of results. Presented selected issues of parametric description of gained results. With measurements as the basis, the relationships, first, between the electric motor's efficiency and temperature, and second, between both the applied power and the power output (effective power) and the ambient temperature have been found. The most important findings of the testing work are, first, that the pressure does not affect the characteristics of the electric motor's performance and second, determination of how temperature affects these characteristics. The results gained have formed the basis for the most vital flight parameters of electrically driven aircraft to be found, including the energy consumption essential for the flight range and endurance. All these findings give grounds for standardization calculations that consist in recalculation of characteristics determined in the course of aircraft flight-testing. Because of their representativeness, they also prove good illustrative examples to demonstrate properties of aircraft's electric propulsion system.

***Keywords**: electric motor, physical parameters of the air, efficiency and power of electric motor*

1. Introduction

Any aircraft has to be subjected to extensive testing program to have both the flying qualities determined and operational safety checked. One of the most vital stages of the testing work is flight tests. They allow us to compare actual flying qualities of the aircraft with the specifications-based ones used as the basis for the design and construction. Flight tests provide the ultimate evaluation and assessment of the whole, very complicated and hence, complex process of originating an aircraft. They also remain indispensable throughout the whole process of aircraft operation and maintenance, since they are a source of many and various data on the aircraft's current health/maintenance status.

One of the components of the flight testing cycle is test flying under different weather conditions. Differences in weather conditions may result from short-term variations, changes due to seasonal variations, and those occurring in different climatic zones, where the flight testing work may be carried out. Therefore, it is absolutely necessary to apply such testing methods that would allow the results gained to be standardized and reduced to those recognized as conditions of reference. Such conditions have been described by the International Standard Atmosphere (Standard Atmosphere).

Correct definition of standardized operational characteristics of an aircraft depends on the knowledge of how the whole system, i.e. the aircraft responds to changes in temperature and pressure. In particular, this refers to the propulsion system. Interrelationships between particular characteristics can be established in the analytical way. However, experimental tests remain the most reliable source of information. Since program-generated changes in physical conditions are quite possible, and also, because of the chance to eliminate some selected side effects, laboratory tests prove advisable and useful. It refers, of course, to situations when such experiments are possible and economically justified.

The above-presented circumstances have occurred for the case discussed in this study. While testing electrical propulsion systems of aircraft, the question of the object's scale (size) plays minor role, at least because of the simplified mechanical structure of the system. Therefore, suitable experiments may be carried out with standard laboratory devices engaged. With this concept in mind, a program has been developed at AFIT of testing an electrical motor used in the propulsion system of an unmanned aerial vehicle. A test stand has been constructed to conduct suitably prepared experiments.

2. Methodology of laboratory experimental tests

The available and analysed literature lacks information on the effect of environmental conditions upon the operation of electric motors used in aircraft propulsion systems. For that reason, an effort was made to carry out tests to find possible and probable relationships between characteristics of the ambient air and power of the electric motor. The object under examination was a brushless DC motor AXI 2820/14 of 360 W power.

2.1. Test stand

Since there is no chance to mount large objects in the already existing facilities, decision was taken to conduct tests with a motor from the mini UAV's electric propulsion system. With respect to the assumed testing program, this motor satisfies specified requirements for representativeness of the model object. To carry out experimental tests, an motor test bench has been designed and constructed. Fig. 1 shows this test bench. An electric brake, i.e. a resistance-loaded electric motor was used as the receiver of energy from the motor under examination. After preliminary tests the proper testing work was started. These tests were conducted with the motor test bench placed within the environmental (barostatic) chamber. The power supply system, the resistance-loading unit and the data recording system remained outside the chamber.

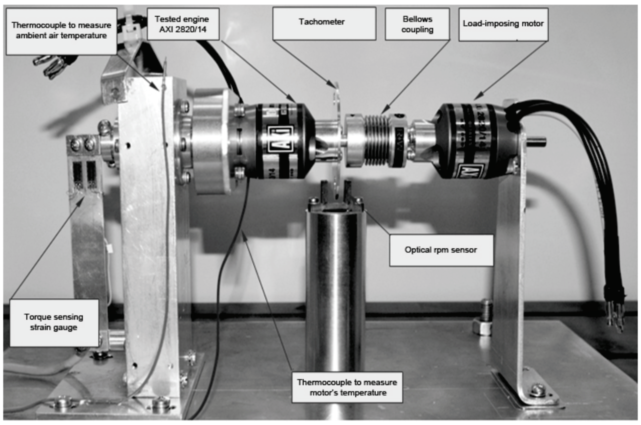

Fig. 1. The measuring bench to examine characteristics of the electric motor

Figure 2 shows the diagram of the measuring system arranged for the proper testing work. All the tests through, the temperature and pressure are computer readjusted according to the settings of the autonomic controller (ChCtr) of the climatic test bench. Variations in atmosphere characteristics inside the chamber are continuously recorded. By means of digital recording systems (digital multimeters – DMM) collected are the motor's (EM) supply voltages and currents, and corresponding values of the electric brake (EB) loading characteristics. The anti-torque produced by the running motor is measured with a set of strain gauges (SG) placed on the motor support. Rotational speed is found from data collected by the diode revolution counter (RC). Additionally, temperature is measured at some selected locations on the motor itself, motor base and components of the barostatic (environmental) chamber. Data Acquisition Cards NI 9211 and NI 9205 of the National Instruments NI cDAQ-9172 chassis (module) and the strain-gauge measuring bridge (MBr) are used to record measuring signals from test gauges. The NI 9211 Data Acquisition Card is used to process and record data from measuring thermocouples (type K, in the 0.5 mm protection tube and teflon-coated 2 x 0.1 mm), whereas the NI 9205 – to record voltage signal from the revolution counter (RC). The measuring bridge (MBr) is used to supply the strain gauges with current and to record strain-gauge signals.

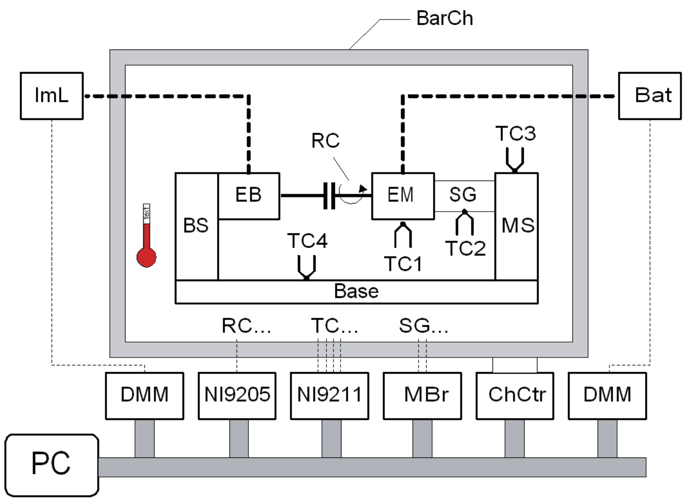

Fig. 2. Diagram of the testing system: BarCh – Barostatic (Environmental) Chamber, EM – Electric Motor, EB – Electric Brake, Bat – Battery, ImL – Imposed Resistance Load, MS – Motor Support, Base, BS – Brake Support, SG – Strain Gauges, TC – Thermocouples, RC – Revolution Counter, DMM – Digital Multimeter, NI 9205, NI 9211 – Data Acquisition Cards, MBr – Measuring Bridge), ChCtr – Barostatic (Environmental) Chamber Controller, PC – Personal Computer (the measuring system controller)

The system in question allows of what follows:

- the control over the full-range variations in characteristics of the so-called standard atmosphere (troposphere), i.e. temperature and pressure inside the barostatic chamber,
- taking records of temperature and pressure variations inside the chamber,
- the direct measurement of deformations of the motor support, which allows the motor-produced anti-torque to be determined,
- the measurement and recording of characteristics of motor current supply, synchronized with the measurement and recording of electric brake (EB) imposed load values.
- the with the above-mentioned measurements synchronized measurement of rotational speed values plus simultaneous recording thereof,
- the measurement and recording of temperature with the multichannel recording system engaged.

The recorded data are recalculated in real time to find values of the selected test parameters. The record as a whole is handled after the recording process is over. The whole system, i.e. the hardware and the software, can be re-configured and adjusted to new testing needs.

2.2. Measuring procedure

The motor was supplied with direct current (DC); its voltage U and intensity I were measured. This enabled the applied power to be calculated:

$$N_d = U \cdot I \,. \tag{1}$$

The motor was loaded by the receiver connected via a bellows coupling. The anti-torque M and the rotational speed ω [rad/s] were measured throughout the tests, which enabled the power output (effective power) of the motor:

$$N_e = M \cdot \omega \tag{2}$$

and its efficiency:

$$\eta = \frac{N_e}{N_d} = \frac{M \cdot \omega}{U \cdot I}, \tag{3}$$

to be calculated.

All the tests through, the temperature and pressure are computer readjusted, according to a preset program, to determine how these quantities affect characteristics of the motor operation. The scope of temperature and pressure variations covered the range of changes typical of the standard atmosphere (ISA). As early as at the stage of preliminary tests it became clear that pressure did not affect power levels and efficiency of the motor. Hence, further measurements were taken to find the effect of temperature.

2.3. Selected issues of parametric description of gained results

Electrically driven airplanes are power supplied from batteries, capacity of which severely depends on temperature. Fig. 3 illustrates this statement. It has clearly been shown that decreasing temperature reduces capacity of batteries. This, in turn, has adverse effect on the flight range and endurance. At the same time the motor efficiency decreases, which means that for the same power output (effective power) the applied power has to grow. This means further reduction in the flight range and endurance.

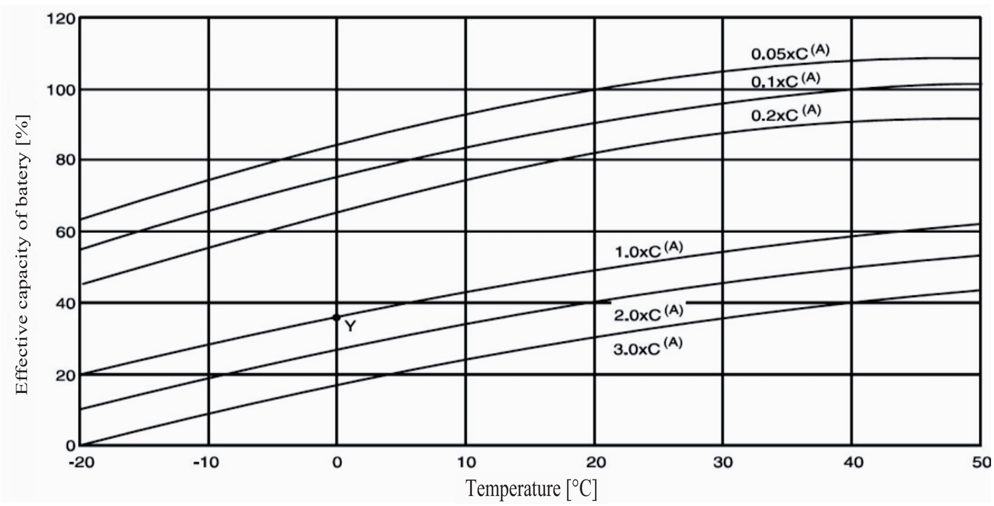

Fig. 3. Capacity of battery against temperature [1]

By analogy to combustion engines, the following terms can be introduced:

- charge consumption per hour I_h – the amount of electric charge consumed by the electric propulsion system through the one-hour flight:

$$I_h = \frac{Q}{t} \qquad \left[\frac{\mathrm{C}}{\mathrm{h}}\right], \tag{4}$$

where:

Q – denotes electric charge,

T – time expressed with flight hours.

- charge consumption per one kilometre I_k – the amount of electric charge consumed by the electric propulsion system over the flight distance of one kilometre:

$$I_k = \frac{Q}{L} \qquad \left[\frac{\mathrm{C}}{\mathrm{km}}\right], \tag{5}$$

where:
L – denotes distance.

- specific electric-charge consumption i_j – the amount of electric charge consumed by the electric propulsion system for one flight hour to produce one power unit:

$$i_j = \frac{I_h}{N_e} \qquad \left[\frac{\mathrm{C}}{\mathrm{W \cdot h}}\right]. \tag{6}$$

The following relationship defines dependence between the charge consumption per one flight hour and per one kilometre of flight distance:

$$I_k = \frac{Q}{L} = \frac{Q}{V \cdot t} = \frac{I_h}{3.6 \cdot V} \qquad \left[\frac{\mathrm{kg}}{\mathrm{km}}\right], \tag{7}$$

where the multiplier 3.6 is used if the flight speed is expressed in [m/s]. It does not appear for the speed expressed in [km/h].

The maximum flight range is reached when the electric charge consumption per one kilometre of flight distance is minimal. If a horizontal flight is to be considered, the electric charge consumption per one kilometre can be shown with account taken of both the specific electric charge (i.e. 'fuel') consumption and characteristics of the airplane and the propeller.

After eq. (7) has been rearranged, with eq. (6) applied, one can get what follows:

$$I_k = \frac{I_h}{3.6 \cdot V} = \frac{i_j N_e}{3.6 \cdot V}\ . \tag{8}$$

Then, taking into account equation of the airplane motion that balances powers of the propulsion system and power of the aerodynamic drag $\eta_{sm} \cdot N_e = C_{xa} \dfrac{\rho_H V^3}{2} S = P_{xa} V$, the following expression is arrived at:

$$I_k = \frac{i_j N_e}{3.6 \cdot V} = \frac{P_{xa} \cdot i_j}{3.6 \eta_{sm}} = \frac{mg}{3.6} \frac{i_j}{\eta_{sm} K}\ . \tag{9}$$

While deducing this relationship, account was taken of the following dependences:

- the motor's power output (effective power) equals $N_e = C_{xa} \dfrac{\rho_H V^3}{2} S = P_{xa} V$,
- the lift-to-drag ratio of the airplane in horizontal flight equals $K = \dfrac{C_{za}}{C_{xa}} = \dfrac{P_{za}}{P_{xa}} = \dfrac{mg}{P_{xa}}$.

For airplanes with electric propulsion system, the minimum charge consumption per one kilometre of flight distance is reached when $\dfrac{i_j}{\eta_{sm} K}$ takes the minimum value. If we assume that i_j=const and η_{sm}=const, the maximum range is reached for the maximum lift-to-drag ratio. The condition is satisfied in flight at the optimum angle of attack.

3. Findings and discussion

In Fig. 4-6, all the measured values have been plotted against time. The full-cycle measurement took approx. 170 min. Over this time interval, the ambient temperature was subject to cyclic changes within the range of 230 K through 328 K (-43°C through 55°C). Fig. 4 shows the electric motor's temperature was higher than the ambient temperature throughout the whole measuring cycle. The difference was approx. 14 K. It results from losses in energy delivered to the motor. This is confirmed with Fig. 5 that shows variations in the applied power N_d, which is higher than the power output (effective power) N_e. It can be easily noticed that some decrease in temperature results in an increase in the applied power and, at the same time, reduction in the power output (effective power); hence, the motor efficiency decreases as the temperature decreases, which has been demonstrated in Fig. 6.

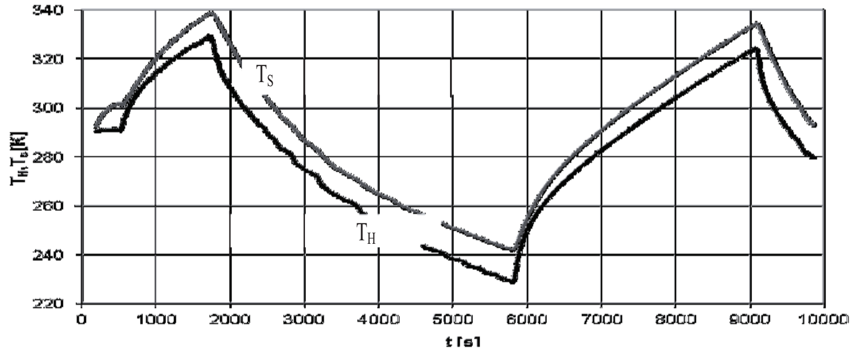

Fig. 4. Variations in ambient temperature $T_H(t)$ and temperature of the electric motor $T_s(t)$

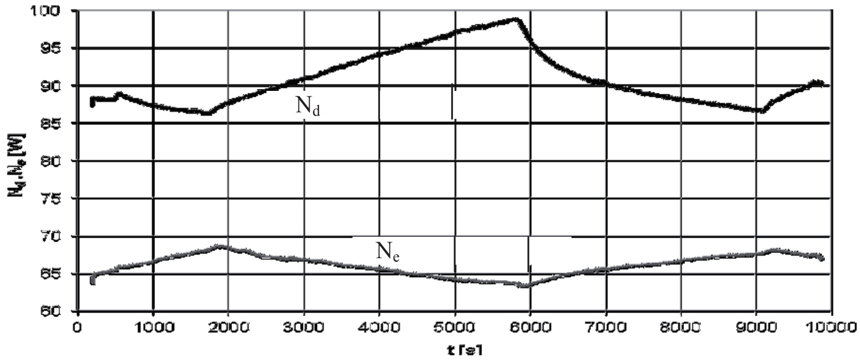

Fig. 5. Variations in applied power $N_d(t)$ and power output (effective power) $N_e(t)$

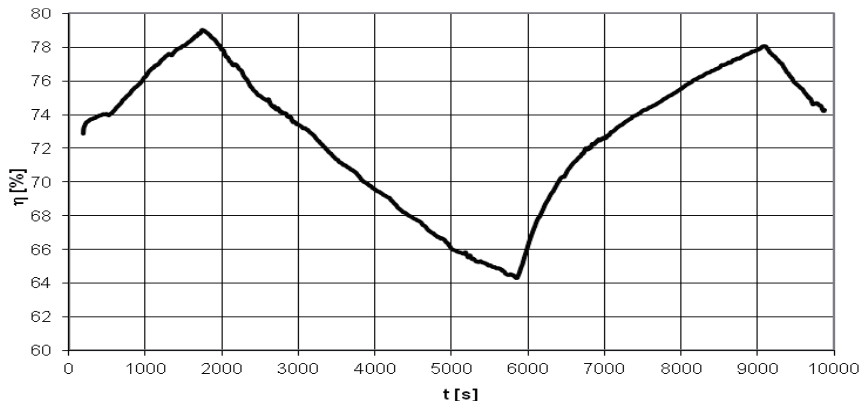

Fig. 6. Variations in efficiency of the electric motor N_d (t)

Since the ambient temperature was the factor effecting variations in measured characteristics of the motor operation, curves have been plotted to show relationships between the motor's temperature T_s, powers N_d and N_e, efficiency η, and temperature T_H. They are shown in Fig. 7-9. Fig. 7 proves an explicit relation between temperatures T_s and T_H. At the same time, clearly noticeable is the hysteresis. The figures in question also show the line approximating the results gained.

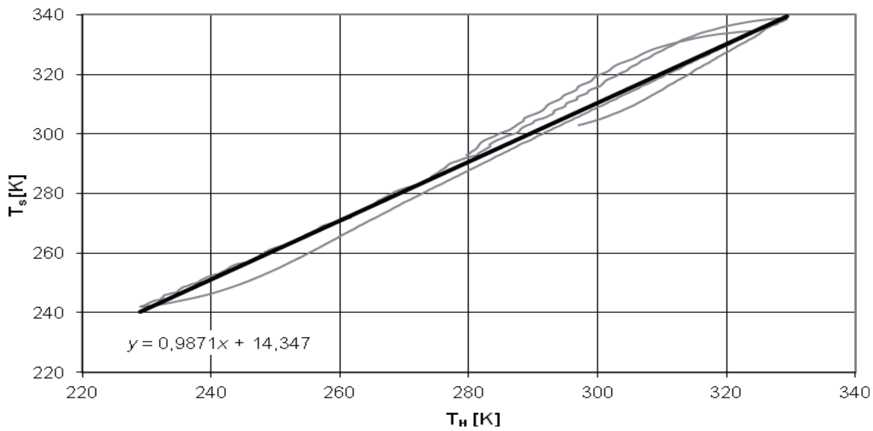

Fig. 7. Dependence of motor's temperature T_s on ambient temperature T_H

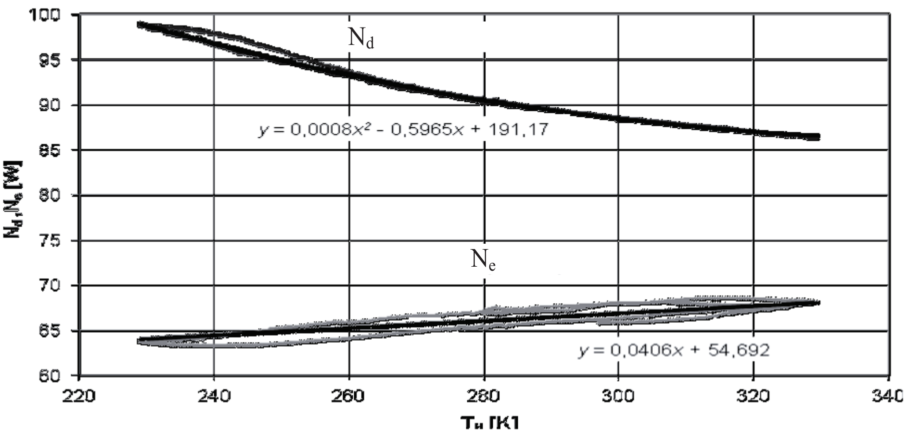

Fig. 8. Dependence of the applied power N_d and power output N_e on ambient temperature T_H

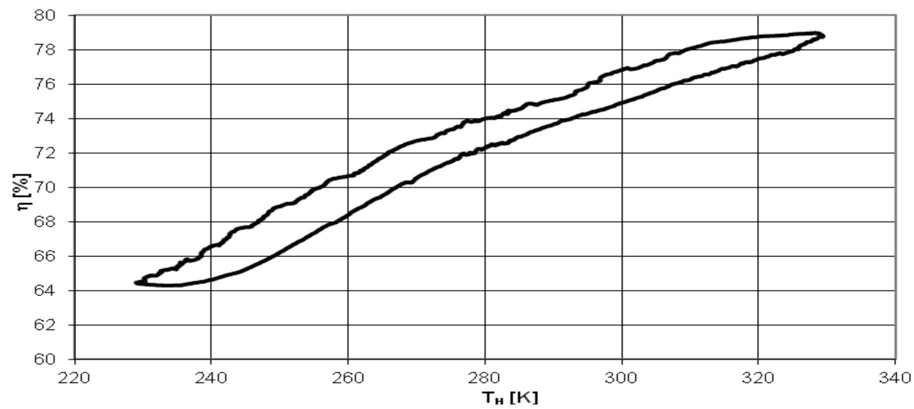

Fig. 9. Dependence of the electric motor efficiency η on ambient temperature T_H

Figure 10 shows the experimentally found dependence between the i_j and the motor speed (revolutions per time unit). It also demonstrates a curve that approximates variations in motor efficiency.

4. To recapitulate…

The paper has been intended to discuss the question of laboratory tests of the aircraft's electric propulsion system. The scope of experiments was limited in practice to testing the electric motor AXI 2820/14. Due to operating conditions of aircraft, the testing work program takes account of how temperature and pressure affect the motor's performance characteristics. To carry out the tests, a test bench was constructed. The tests themselves were performed in the barostatic (environmental) chamber. The most important findings of the testing work are, first, that the pressure does not affect the characteristics of the electric motor's performance and second, determination of how temperature affects these characteristics.

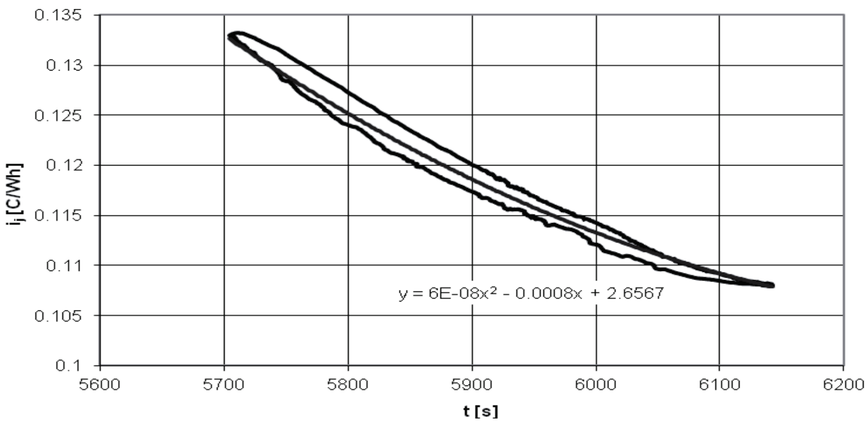

Fig. 10. Specific electric-charge consumption

All these findings give grounds for standardization calculations that consist in recalculation of characteristics determined in the course of aircraft flight-testing (see [2]). Because of their representativeness, they also prove good illustrative examples to demonstrate properties of aircraft's electric propulsion system.

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