DIAGNOSTIC INVESTIGATIONS OF TURBOJET INJECTORS

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Abstract

The basic aim of injectors is to supply a specified amount of fuel to the turbine engine combustion chamber. The fuel should be atomized to the extent which enables its evaporation and helps to produce a homogenous mixture of fuel vapour and air, thus ensuring high efficiency of the combustion process. The article contains the review of methods and diagnostic equipment used in Aviation Overhaul Works (Lotnicze Zakłady Remontowe) in assessing the suitability of turbine jet as well as turboprop and helicopter engines sprayers. Injectors are evaluated on the basis of their fuel delivery Q(p) which determines the volume of fuel sprayed in the time unit, the spray cone angle β(p) and the parameter J(p) which describes the asymmetry in the circumferential spray density distribution j(α). These parameters are dependent both on structural characteristics of the sprayers as well as on fuel delivery pressure p in the fuel supply pipe. In the standard diagnostic stations, the measurement of fuel delivery Q(p) is carried out only for the two fuel supply pressures, corresponding to the extreme engine ranges, that is the rotational speed of the idle running n_{bj} *and maximum rotational speed* n_{max}*. Injectors undergo the leak test at the fuel pressure 5 to 10 times bigger than the nominal value. Tolerances adopted by the producers for the measured parameters characterizing the injectors are also presented.*

***Keywords**: aircraft turbine engines, fuel injectors, fuel spray diagnostics*

1. Introduction

Turbine engine injectors are the last executive component in the fuel system. They function properly only when the macroscopic parameters of the spray are, within the accepted tolerances, in line with the reference values specified by the manufacturer. Directly before their installation, sprayers undergo control carried out both by the manufacturer and the overhaul plants. Measurement stations to diagnose aircraft engine sprayers used in the overhaul plants allow only to measure the basic macroscopic parameters of the spray. Fuel delivery, circumferential regularity of spraying and spray cone angle perceived as the function of supply pressure are examined. The leak test is also performed.

2. Fuel spray parameters and the applied measurement methods

Injectors are evaluated on the basis of their delivery $Q(p)$, which determines the volume of the fuel sprayed in the unit of time, spray cone angle $\beta(p)$ and parameter $J(\alpha, p)$, which characterizes spatial inequality in the process of fuel spraying [1-4]. The parameters depend on both the structural characteristics of sprayers as well as on the pressure p of the fuel in the supply pipe.

Expense $Q(\Delta p)$ - determines the entire volume V of the fuel sprayed in the unit of time τ depending on the pressure difference Δp:

$$\Delta p = p_1 - p_2, \tag{1}$$

specified by the value of pressure in the output cross-section of sprayer p_1, and pressure behind the nozzle p_2. In the static diagnostic test, that is in the case when fuel is sprayed into the stationary air stream, pressure p_2 is equal to the atmospheric pressure p_a. The operating range of main sprayers of turbojet engines is $p_1 = 1\text{-}5$ MP. The conclusion that follows is that $p_1 >> p_a$, which in turn allows to adopt the approximation:

$$\Delta p = p_1 - p_a \approx p_1 = p \text{ and } Q(\Delta p) \approx Q(p). \tag{2}$$

The parameter $Q(\Delta p)$ can be measured by a volumetric method, flow method (with the use of orifices, rotameters and various flowmeters) or in an indirect way – by a comparative method. In the case of a volumetric method, the fuel delivery is determined from the definitional relationship.

$$Q(\Delta p) \approx Q(p) = V(\tau)/\tau. \tag{3}$$

Fuel is sprayed during time τ into the measuring vessel, in which its volume $V(\tau)$ is determined. This method is time consuming and requires that a substantial amount of fuel is atomized. Its basic advantage is the absolute character of the measurement and its high accuracy. For these reasons, it is used to validate results obtained indirectly or with the use of flowmeters.

In the comparative method, first we measure the fuel pressure p_w in front of the model injector of nominal expense $Q_n(p_w)$ and next the pressure p_b in front of the injector examined. If those pressures are the same, that is $p_b = p_w$, it is consequently assumed that $Q(p_b) = Q(p_w)$ as the fuel delivery of the sprayer is defined by the relationship:

$$Q(p) = \mu F \sqrt{\frac{2(p - p_a)}{\rho}}, \tag{4}$$

where:

μ - coefficient of the flow rate through the injector holes,
F - total cross-sectional area of the holes,
ρ - fuel density.

In the flow method, we use reducing pipes which ensure high accuracy of measurement for big fuel delivery $Q(p)$. Rotameters and flowmeters are usually less accurate.

Spray cone angle β - is a vertex angle of the stream of droplets flowing out of the nozzle (Fig. 1), which affects the right fuel combustion process in the combustor. The measurement of the spray angle β is performed by manually setting the movable hand of the protractor tangentially to the generatrix of the spray cone (Fig. 2-5). This method is not precise. The results are not unequivocal and may be somewhat arbitrary. The main source of error may be the fact that the spray contour is slightly deformed and not very clear, especially for big fuel delivery $Q(p)$.

The measurement errors strongly depend on the measurement method. Photographic registration of the spray angle enables to determine β angle more accurately owing to the careful analysis of images. This method is not applied because of the complicated structure of the measurement station and high susceptibility of the optical components to the droplets of hydrocarbon fuel.

Circumferential spray density distribution $j(\alpha)$ - allows to estimate the symmetry of the stream of droplets with respect to its axis. The distribution should be uniform; however, due to technological errors and mistakes in the injector installation, the stream may be significantly distorted. While the injector is in service, the circumferential spray inequality may appear due to erosion of the sprayer components, settling carbon deposit on the nozzle surface or pollution of the spraying duct. The values $j(\alpha)$ are determined in the diagnostic test in which the fuel is sprayed into a cylindrical vessel divided into sectors with identical central angle α (Fig. 1b).

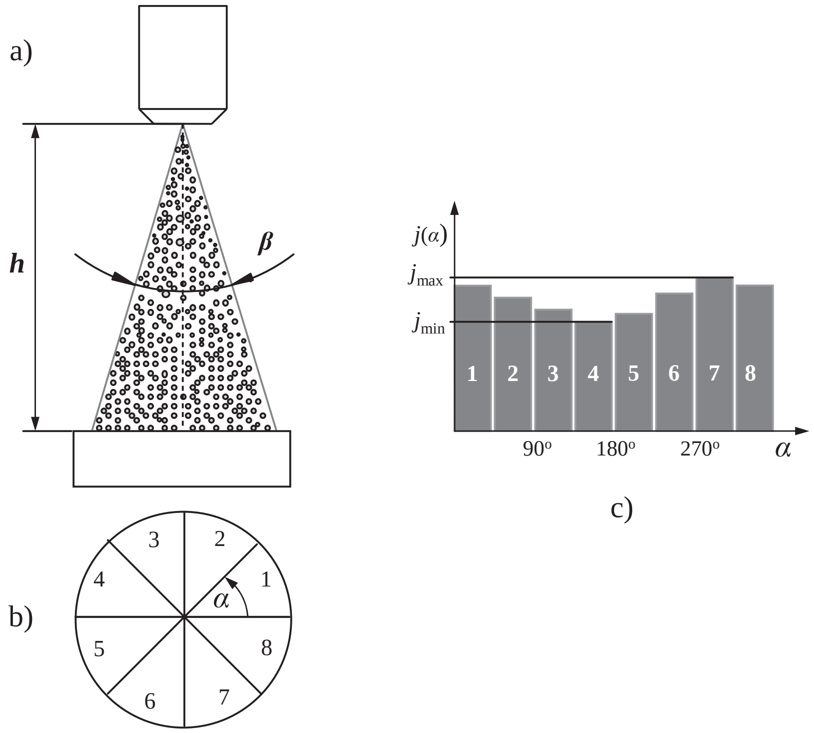

Fig. 1. The spray cone angle β and circumferential spray density distribution j(α)

The quantitative measure of the asymmetry of the function $j(\alpha)$ is the circumferential spray density inequality J:

$$J = \frac{j_{\max} - j_{\min}}{j_m} \cdot 100\,[\%], \tag{5}$$

which is the difference between the maximum $j_{\max}$ and minimum $j_{\min}$ spray density in the separate sectors (Fig. 1) referred to the average value j_m of the whole measuring cylinder. Typical values of the central angles α of a sector are 60°, 45° and 30°, which means the division of the measuring space into 6, 8 and 12 sectors respectively. The fuel from those sectors flows into measuring vessels, in which the height of the liquid column l_i is determined. The relation (5) can be converted into the form:

$$J = \frac{l_{\max} - l_{\min}}{\frac{1}{n}\sum_{i=1}^{n} l_i} \cdot 100\,[\%], \tag{6}$$

in which the spray density $j(\alpha)$ is replaced by the value $l(\alpha)$ proportional to it.

In aircraft turbine engines too large circumferential inequality of the spraying process may lead to burnout or punctures of the combustion chamber walls.

3. Measurement stations

The article presents diagnostic stations used in Military Aviation Overhaul Works to evaluate the suitability of turbine engines fuel injectors [2]. The design of those stations and the measurement methods applied are very similar. Several functional systems can be distinguished in the structure of the stations. The fuel system consists of: the main tank and possibly of additional overflow tanks, filters, safety valves and hydraulic power system generating appropriate pressure in the fuel supply pipes. In the stationary stations it is usually compression pump and a set of reducers which enables the regulation of the pressure of fuel delivered to injectors. In the mobile stations, the component generating pressure in the whole system is compressed air cylinder. To maintain the temperature of the fuel within appropriate range, heat exchangers, heaters and radiators are used.

3.1. Measuring station ITL WAT

This type of a station (Fig. 2) makes it possible to determine fuel delivery $Q(p)$, spray cone angle $\beta(p)$ and circumferential spray density inequality $J(p)$, which is often referred to as circumferential inequality of the fuel spray. Hydraulic power system consists of compressed air cylinder, check valves, reduction valves, fuel tank and air bleed valve. The tested injector is mounted in the upper part of the measuring chamber (5). An organic glass cover allows the observation of fuel spray. The measurement of the spray cone angle $\beta(p)$ is done by means of movable hand, which is set tangentially to the generatrix of the spray cone. The lower part of the cylindrical chamber is divided into twelve identical sectors of the central angle $\alpha = 30°$. The sectors are connected by separate measuring vessels. The asymmetry of the fuel droplets stream regarding the injector axis is reflected by the uneven filling of the tanks (6).

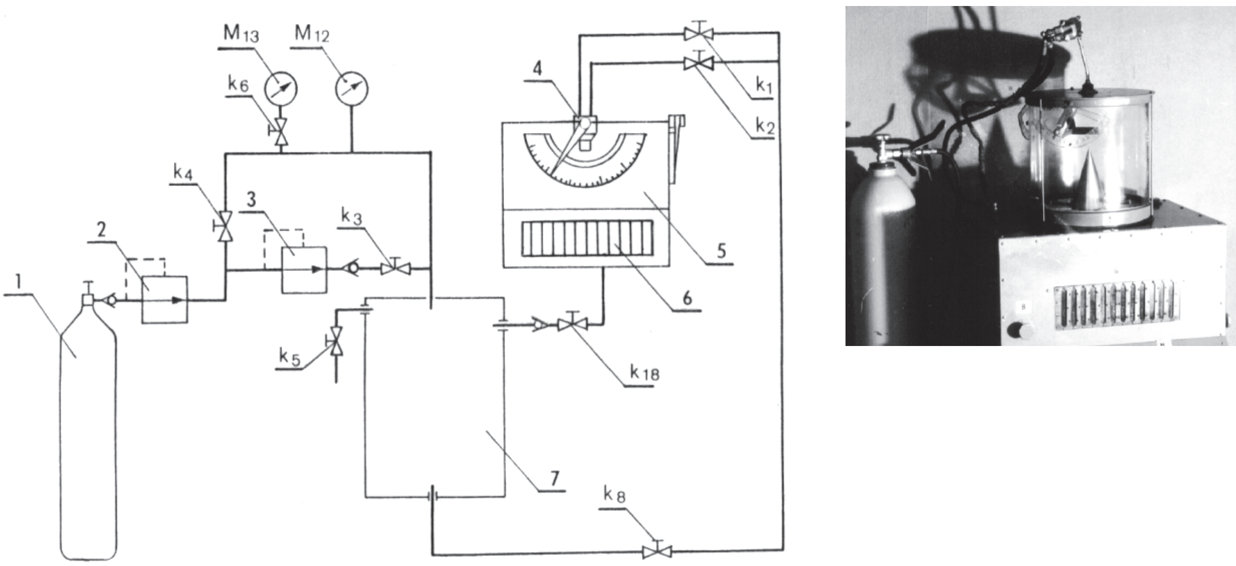

Fig. 2. Measurement station ITL WAT diagram (1 - compressed air cylinder, 2 - control valve, 3 - PU-7 valve, 4 - injector tested, 5 - measurement chamber, 6 - measurement chamber display window, 7 - fuel tank, k_5 – air bleed tank, k_1, k_2, k_3, k_4 k_6, k_8 and k_{18} - fuel supply pipes panel control valves, M12 i M13 – manometers)

This station is currently used in the Aviation Technology Institute of Military University of Technology in Warsaw (WAT) for educational purposes.

3.2. Measurement station W – 1761

The W - 1761 station (Fig. 3) is designed for measuring fuel spray cone angle $\beta(p)$ of main injectors (characterized by a big fuel delivery $Q(p)$) as well as startup injectors. It is equipped with systems which enable to evaluate the technical condition of fittings and welds of tested injectors in fuel and air leak - proof test. The leak - proof tests are carried out after the discharge outlet of the nozzle has been closed and the fuel pumped at the pressure $p = 5\text{-}10$ MPa, and those steps are followed by the immersion of the sprayer in a tank filled with a liquid and pumping the air at the same pressure.

In the cuboid measurement chamber there are two seatings to mount injectors. The side seating (9) is designed to fit the 16.83.0310 type sprayers whereas the top seating multi-purpose one.

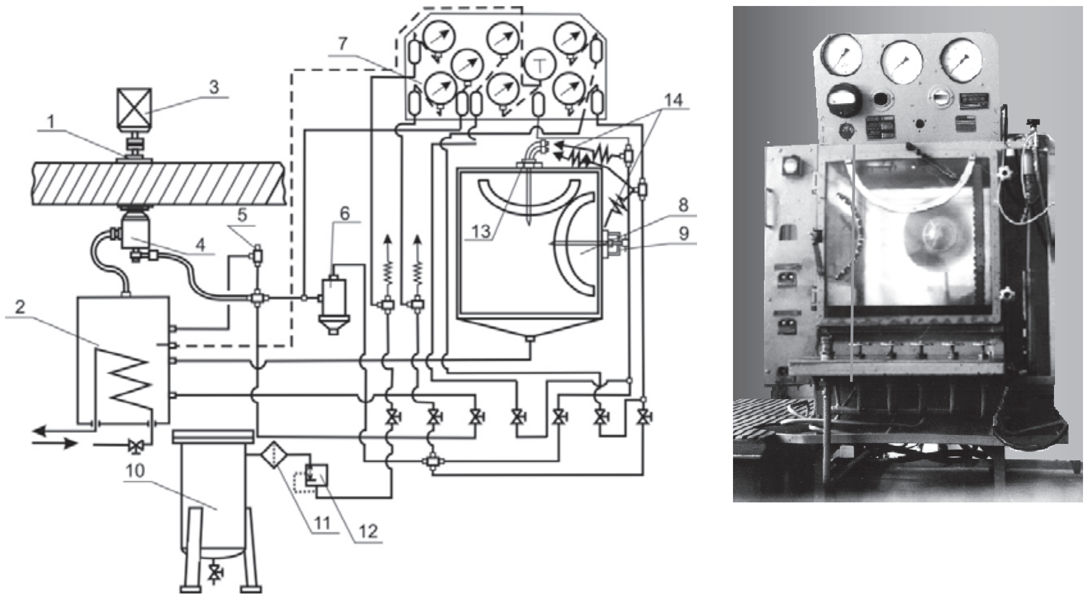

Fig 3. W - 1761 station diagram (1 – pump drive, 2 – fuel tank, 3 – electric engine, 4 – fuel pump, 5 – overflow valve, 6 – filter, 7 – measurement equipment panel, 8 – measurement chamber, 9 – side seating for fitting injectors, 10 – air dehumidifier, 11 – filter, 12 – reduction valve, 13 – injector tested, mounted in the upper seating, hoses linking the injector with the supply pipes)

3.3. Ka - S/W type measurement station

The station of this type enables to diagnose main injectors by measuring fuel delivery $Q(p)$ and fuel spray cone angle $\beta(p)$. It is equipped with the systems which help in carrying out the leak - proof tests. In the measuring system Ka - S/W (Fig. 4), there are three tanks suitable for measuring fuel delivery corresponding to the minimum rotational speed of the engine n_{bj} (7), maximum rotational speed of the engine $n_{max,}$ (5) and the parameter $J(p)$ which defines the circumferential inequality of spray (6). The use of tanks with increased volume allows to extend the time of filling the tanks up to 2-3 min and to increase the accuracy of the fuel delivery measurement $Q(p)$ for two pressures of fuel supply, typical for both extreme ranges of engine running.

Due to compact design (the fuel pump with the engine is the only separate component), this stand may be movable.

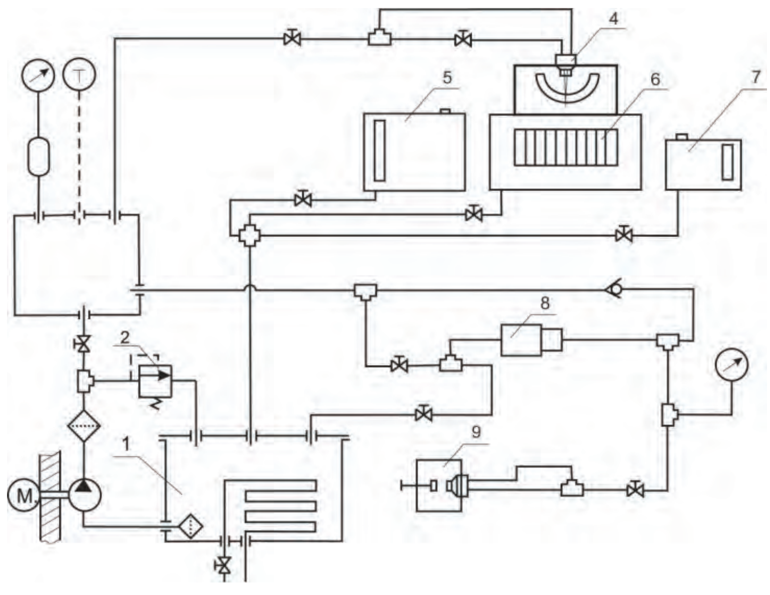

Fig. 4. Ka - S/W station diagram: (1 – tank with radiator, 2 – safety valve, 3 – equalizing tank, 4 – tested injector, 5, 6, 7 – measuring vessels, 8 – pressure cylinder, 9 – injector grip to carry out leak proof test)

3.4. URS-97-R type measurement station

It is designed to measure the fuel delivery $Q(p)$ of main and startup sprayers as well as fuel spray cone angle $\beta(p)$ (Fig. 5). The measurement of the fuel delivery is carried out by volumetric method:

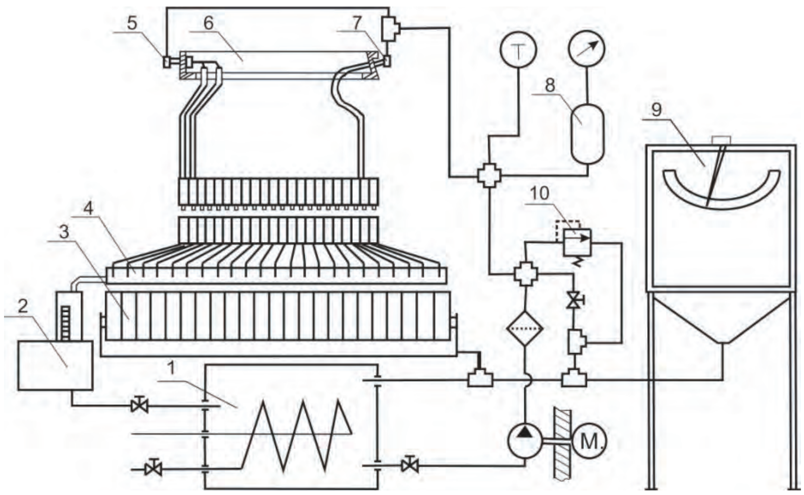

Fig. 5. URS-97-R type station diagram (1 – heat exchanger, 2,3 – measuring tanks, 4 – downpipe, 5 – tested injector, 6 – ring to install eighteen injectors, 7 – startup injector, 8 – cylinder, 9 – measuring chamber, 10 – safety valve)

This stand enables also the measurement of total fuel delivery of the supply manifold, which consists of twelve main sprayers and six startup sprayers.

3.5. W-1762 type measurement station

The diagnostic station type W-1762 (Fig. 6) enables to measure the fuel delivery $Q(p)$ and circumferential inequality of main and startup sprayers. In the applied comparative method, the measurement of fuel pressure p_w in front of the model sprayer of nominal expense $Q_n(p_w)$ is performed first, then the pressure p_b in front of the sprayer tested is taken. If the pressures are equal $p_b = p_w$, it is then assumed that $Q(p_b) = Q_n(p_w)$, as the fuel delivery of the sprayer is defined by the relation (4). The injector tested is considered to be suitable when the pressure difference $\Delta p = p_b - p_w$ is within the acceptable range, defined by the performance standards.

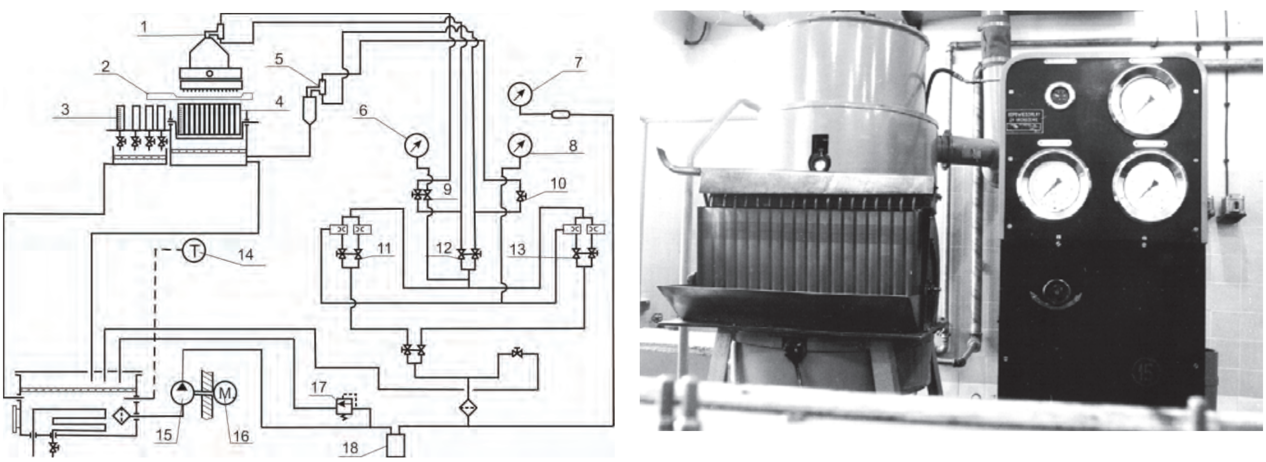

Fig. 6. W-1762 type station diagram (1 – tested injector, 2 – drain pipe, 3 – measuring vessels, 4 – measuring tank, 5 – standard sprayer, 6,7,8 - manometers, 9,10,11,12,13 – supply bus separating valves, 14 – thermometers, 15 – pump, 16 – engine, 17 – overflow valve, 18 – equalizing tank)

The advantages of the comparative method result from the simplified technique of measurement and considerable reduction of the testing time (thus the amount of fuel is also reduced), because only nominal fuel delivery $Q_n(p_w)$ of the model sprayer is measured with the use of volumetric method.

4. Summary

The presented diagnostic stations are relatively simple. Such an opinion refers not only to the applied measuring methods but also to their technical implementations. The need to read values from analogue gauges with pointers as well as the subjective role of the examiner during the evaluation of the spray cone angle $\beta(p)$ cause that the measurement accuracy is not high (from some to several per cent).

Diagnosis carried out by the methods described does nor contain information about radial spray density distribution $j(r)$, which together with circumferential distribution $j(\alpha)$ allows to fully evaluate the spray cone asymmetry.

It appears that tolerances ranges of parameters characterizing sprayers (determined by manufacturers) are too large. The injectors regarded as suitable are characterized by circumferential inequality not bigger than $J_{max} = 20\text{-}35\%$. Fuel injectors, for which $J > J_{max}$ are not allowed for use, as considerable asymmetry of the sprayed stream may result in overheating and puncture of the combustor wall.

The spray cone should be symmetrical towards the sprayer axis, and the angle β should be within the range $(\beta_{max} - \beta_{min})/\beta_{nom} = 10\text{-}20\%$. The measurement of this parameter is encumbered with the biggest error. This results from the method applied which is of too arbitrary character. The spray cone generatrix edge is easily visible for startup sprayers of little fuel delivery. Main sprayers operate at substantially higher pressures, and their maximum expenses are greater by even two orders of magnitude, which lead to the disappearance of the clear edge of the sprayed fuel stream.

The smallest tolerance range that has been adopted for the parameter characterizing a sprayer, is the fuel delivery, as $(Q_{max} - Q_{min})/Q_{nom} = 2\text{-}10\%$.

If the measured parameters $Q(p)$, $\beta(p)$ and $J(p)$ are within the accepted limits of tolerance, the injector is considered suitable and allowed for use.

The assessment of suitability carried out in this way does not take into account a very important parameter characterizing properties of each sprayer, that is the extent of atomization of the liquid. In no station described above it is possible to define, even approximately, the substitute of fuel droplets diameter D_z, which is a real diagnostic gap. It thus makes it necessary to assume that the sprayer suitability evaluated on the basis of parameters $Q(p)$, $\beta(p)$ and $J(p)$ implies that the extent of atomization of droplets in the sprayed fuel stream is similar to the nominal one. However, the optical measurement results and the operation practice do not support this assumption [5].

While describing diagnostic stations and tolerance ranges for parameters that characterize fuel spray properties, data included in the studies [6-10] were used.

The above overview of diagnostic stations has been presented in connection with research and construction works are aimed at partial at least automation of the process of evaluating the turbine engine fuel sprayers suitability, which are in operation in the Republic of Poland Air Force. It also appears that the assessment of the circumferential inequality of the fuel spraying process by determining the value of the parameter $J(p)$ should be supplemented by an additional parameter, which will define the direction of the deformation of the fuel spray cone axis.

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