STUDY ON KEROSENE ATOMIZATION PROCESS UNDER A HIGH SPEED AIR STREAM

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Abstract

For the needs of fuel-injection system development for the experimental detonation combustion chamber with a rotating detonation (PoiG – Project: „Turbine engine with detonation combustion chamber") a series of experiments with injection of kerosene under a high speed air stream was performed at the Institute of Aviation. The proper preparation of combustible mixture is very important for the initiation and sustenance of a rotating detonation. The task in case of kerosene-air mixture is far more difficult than for mixtures of hydrogen-air or kerosene-oxygen. A simple stream injector has been tested as a base system, and the kerosene was injected perpendicular to the air stream vector directly from the plane wall of the constant cross-section channel. The process of injection and atomization of kerosene was observed in the special transparent visualization chamber, enabling the spray observation of two mutually perpendicular directions. In subsequent experiments air pressure, air temperature and air flow velocity as well as and injection pressure of kerosene were varied. The tested process was photographed and, in case of chosen experiments, filmed using a high-speed digital camera. The surveys were aimed at identifying and assessing of following parameters of fuel atomization process: the range of the fuel stream and filling grade of research channel with aerosol, aerosol homogeneity and the size of forming it droplets, the possible presence of fuel streams flowing down the walls of channel. The resulting photos allowed for more comprehensive, but only a qualitative assess of the spraying process, while the filmed small regions of visualization chamber allowed the counting down and dimensioning of droplets. This paper presents a test facility and measuring techniques applied during the research activity and selected results of carried out tests.

Keywords: *transport, aircraft engine, the combustion chamber, fuel atomization, rotating detonation*

1. Introduction

In order to assort the parameters of the injection system destined for the experimental detonation combustion chamber of GTD-350 - engine the formation process of kerosene-air mixture was tested. Under the test was a simple stream-type injector. The kerosene was injected perpendicularly from the wall into the air stream flowing in a rectangular channel at velocities of approximately 50, 100 or 150 m/s. The primary series of experiments comprised injections perpendicular to the air stream. The process of kerosene-air mixture created in the chamber was observed via visualization chamber having transparent walls and photographed or filmed using high-speed digital camera. In some experiments, this process was photographed in two axes simultaneously. The pictures and films were usually taken using penetrating light (shadow method) by means of digital cameras Nikon D300S and Sony α350 both fitted out with "macro" lenses as well as a FASTCAM SA1.1 camera produced by Photron, equipped with ultra-rapid shutter (400 ns) and specialized "macro" lens with dedicated set of strong illumination.

2. Specification of test stand

Figure 1 presents scheme of test facility where the parameters to be measured and recorded are pointed out. Visualization chamber is supplied from thermally insulated air-compressed tank with capacity of 2 m^3. The set of heaters allows heating of air in the tank up to 200°C. The transparent walls of visualization chamber are made of polycarbonate. The measuring region of chamber is 10 mm high and 44 mm width. The outflow from the chamber is throttled by means of interchangeable inserts (critical orifice) in order to achieve the required airflow rate at its measuring part (see Fig. 2). The kerosene injected into air stream (Jet A) is pushed out from the fuel tank using compressed nitrogen. Solenoid valves 1 and 3, which are characterized by short operation time, are operated electrically.

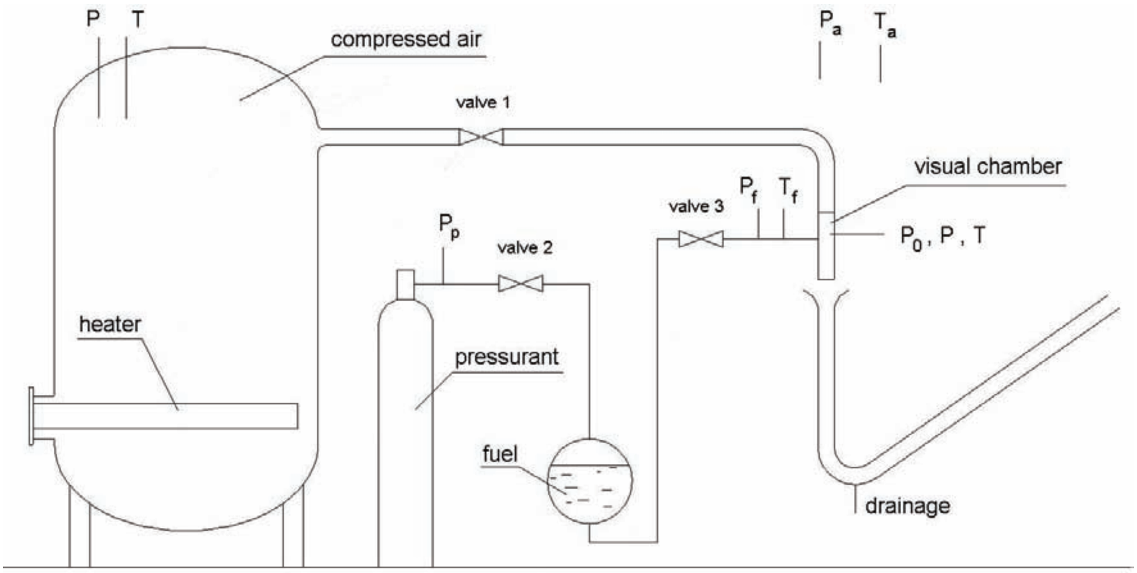

Fig. 1. Scheme of the test bed

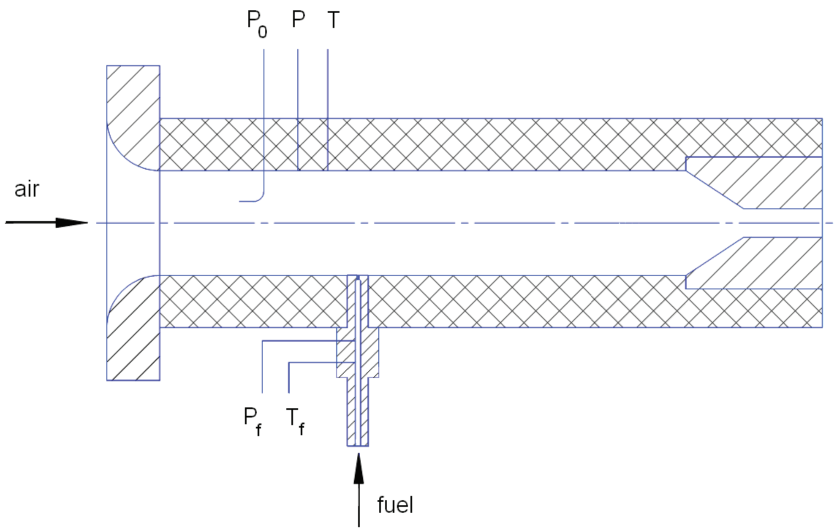

Fig. 2. Outline o f visualization chamber (rotated view - actual position: vertical)

3. Expected parameters of the observed process and criteria for its evaluation

The basic parameters to be determined during tests of injectors are as follows: size (diameter) of droplets, change of their geometry along the longitudinal dimension of chamber (due to disintegration and possibly evaporation) and the distribution of the droplets in the chamber space (homogeneity of the mixture). In this case the significant problem causes the observation of very small (about 10 microns) and fast-moving (about 100 m/s) objects. At the first, fairly extensive stage of the research the use of cameras was planned expecting recording of blurred cloud of aerosol.

Preliminary assessment of injection quality should be based on two criteria:
1) if the filling up of flow channel with aerosol is complete and uniform enough,
2) if the fuel is noticeable flowing on the channel wall (undesirable case).

In the 2-nd stage of research the filming of chosen experiments using high-speed camera was foreseen and then, as far as possible, analyzing of selected frames in terms of counting and measuring of kerosene droplet size transported in the air stream.

The expected sizes and paths of droplets were estimated using a very simple model of injection, where the instantaneous breakup of the fuel stream into droplets was assumed, which then promptly break up into smaller ones. Approximate, maximal droplet size was estimated using the Weber criterion (We_{cr} = 10-14 for the first form breakup of droplets - so called "bag breakup"). Strict velocity of fuel flow out through injector hole was determined from Bernoulli equation for the set value of injection pressure.

4. Selection of experiment's parameters

Two specific points on GTD-350 engine curve were accepted as the basic: idle and rated continuous power. Approximate engine parameters at these points are shown in Tab. 1.

Tab. 1. Approximate parameters of the GTD-350 engine (standard conditions)

Effective power [hp]	Pressure ratio	h.p. turbine velocity [rpm]	Air stream [kg/s]	Air temp. after compressor [K]	S.f.c [g/hph]	Fuel cons. [kg/s]	Remarks
32	2.2	25650	1.10	390	1625	0.01444	idle
320	5.3	40500	2.04	516	370	0.03289	rated power

During the tests the injectors with holes of nominal diameter of 0.12 mm and 0.15 mm were used (injectors made by electro-erosion method had holes of actual diameter respectively: 0.135 mm and 0.155 mm). Fig. 3 shows the actual characteristics of applied injectors. It is assumed initially, that for the forthcoming, toroidal combustion chamber, the proper number of injection holes should be in range between 30 and 60. This assumption allowed for approximate selection of desired injection pressure value of 45 bars for rated power of GTD-350 engine.

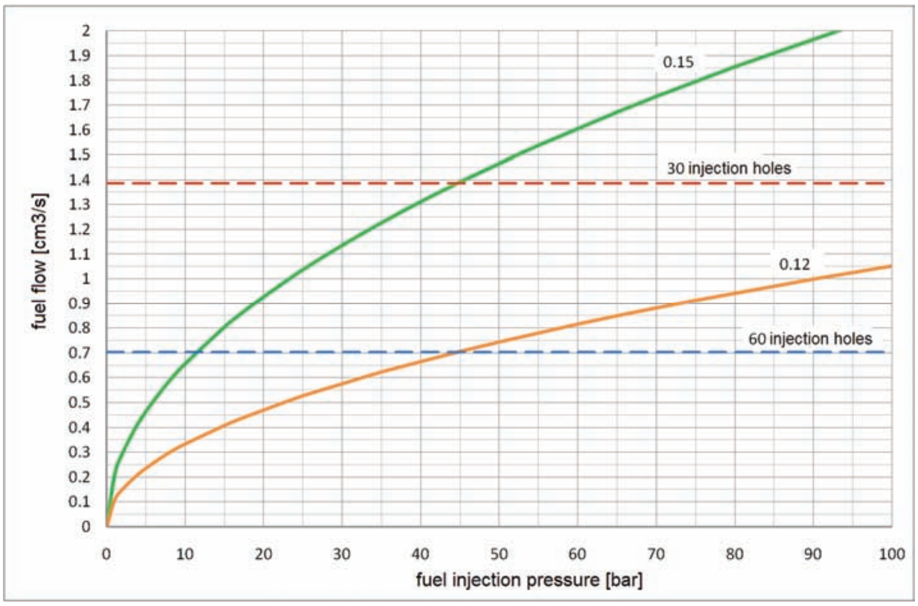

Fig. 3. The characteristics of "0.12"and "0.15' injectors with marked, accepted borderlines (30 and 60 holes) for rated power of GTD-350 engine

Values of air stream velocity (50, 100 and 150 m/s) were adopted on the basis of preliminary accepted geometry variants of detonation chamber. In most experiments, the temperature of the air flowing through the visualization chamber was about 25°C. Some of tests were repeated after warming up supplying air in the tank to about 130-150°C. Such action allowed the air temperature in the visualization chamber to increase to about 70°C (no significant effect on the process was observed). In a series of experiments related to the rated power parameters of GTD-350 engine fuel injection pressure was set up for 30, 45 and 60 bars. The fuel was not heated up prior to injection.

5. Presentation of exemplary results

Parameters of experiment No. 16 (injector "0.12") planned:

- absolute impact pressure of air in the chamber: 5.3 [bar]
- air flow velocity in the chamber: 50 [m/s]
- temperature of air stream in the chamber: 25 [°C]
- fuel injection pressure: 30 [bar]
- fuel temperature: 15-30 [°C]

Parameters of the experiment No. 16 measured/calculated:

- absolute impact pressure of air in the chamber: 5.145 [bar]
- absolute static pressure of air in the chamber: 5.054 [bar]
- average air flow velocity in the chamber: 57 [m/s]
- temperature of air stream in the chamber: 36 [°C]
- absolute pressure fuel injection: 35 [bar]
- fuel injection pressure: 29 [bar]
- fuel temperature: 20 [° C]

Expected parameters:

- approximate injection speed (in acc. with the Bernoulli equation): v = 86.6 m/s
- maximum droplets speed against the air stream (50 m/s): w = 100 m/s
- density of air stream (at 5.3 bar, 516 K - see Tab. 1): r = 3.58 kg/m3
- accepted value of kerosene surface tension [5], [6]: σ = 0.026 J/m2
- calculated droplet diameter for the Weber criterion: Wecr = 10÷14 (critical Weber number is usually taken in this range [1-3]). In this case the Weber number is defined as the ratio of air stream dynamic pressure to droplet surface tension force:

$$We_{cr} = \frac{\rho \cdot w^2 \cdot d}{\sigma} = 10 \div 14 \rightarrow d = \frac{\sigma}{\rho \cdot w^2} \cdot We_{cr} \,. \qquad (1)$$

According to accepted above parameters the biggest droplets are to be expected in the range of 7 to 10 μm. Assuming as simplification the immediate breakup of fuel stream and secondary disintegration of droplets, the trajectories of droplets were estimated using an elaborated model of spherical droplet movement in the air stream. Another criterion for a drop breakup using comparison of the aerodynamic drag force to the force of droplet surface tension shows [1, 4]:

$$\frac{1}{2} \cdot \rho \cdot w^2 \cdot \frac{\pi \cdot d^2}{4} \cdot c_x = \pi \cdot d \cdot \sigma \rightarrow d = \frac{\sigma}{\rho \cdot w^2} \cdot \frac{8}{c_x} \cdot \qquad (2)$$

This equation allows determining an approximate quantity of Cx-coefficient compatible with Weber's criterion. Comparison of relation (1) and (2) shows that the accepted average value We_{cr} = 12 corresponds to Cx = 2/3 (for the same *d*). This value was accepted for calculation of droplets trajectory. Estimated trajectories of droplets of different diameters for the considered case are presented on Fig.4. For comparison, a photo is added below this graph, which presents the actual injection. Both images are positioned regarding size and configuration to match the scale (the arch in the bottom of photograph is a profile of the injector, while the arches and shadings on the top of the photo represent the contours of the blind hole in which the special rod for focusing the camera before the experiment is inserted).

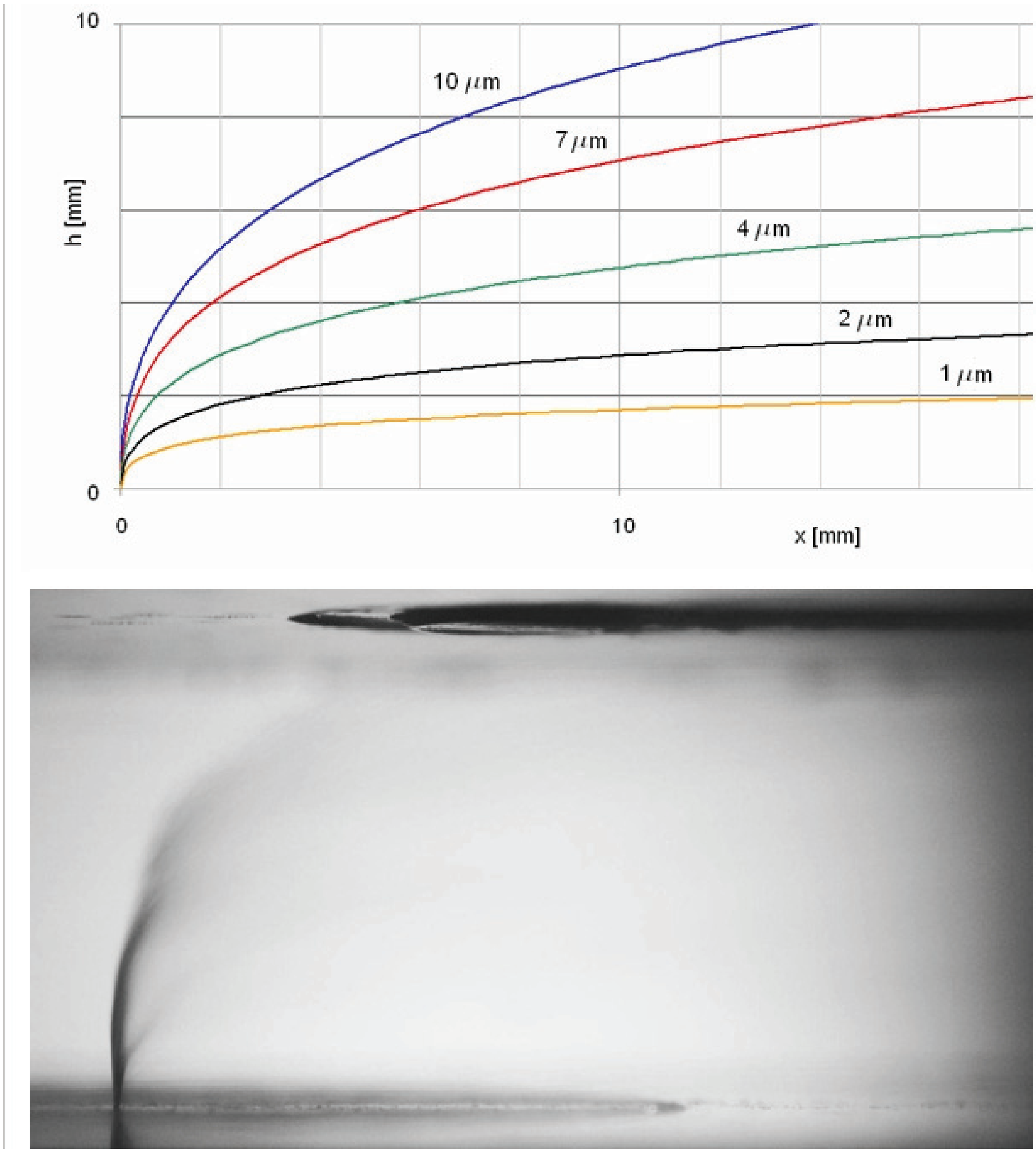

Fig. 4. Experiment No. 16 - the foreseen droplets trajectories in above described experiment combined with a photograph of actual injection

Figure 5 shows a one frame from the film registered using high-speed digital camera, which represents the area of about 6 x 6 mm. Next to the frame a sketch illustrating the location of the image relative to injection hole inside the visualization chamber is placed. Droplets visible on the frame were totted up, measured and treated statistically. Results of counting are shown below in numerical and graphical manner (histogram in Fig. 6).

Results of the frame (1403) processing:

- maximum diameter: 20.41 [μm]
- minimum diameter: 2.09 [μm]
- volumetric mean diameter: 8.02 [μm]
- average surface diameter: 7.61 [μm]
- Sauter mean diameter (SMD): 8.90 [μm]

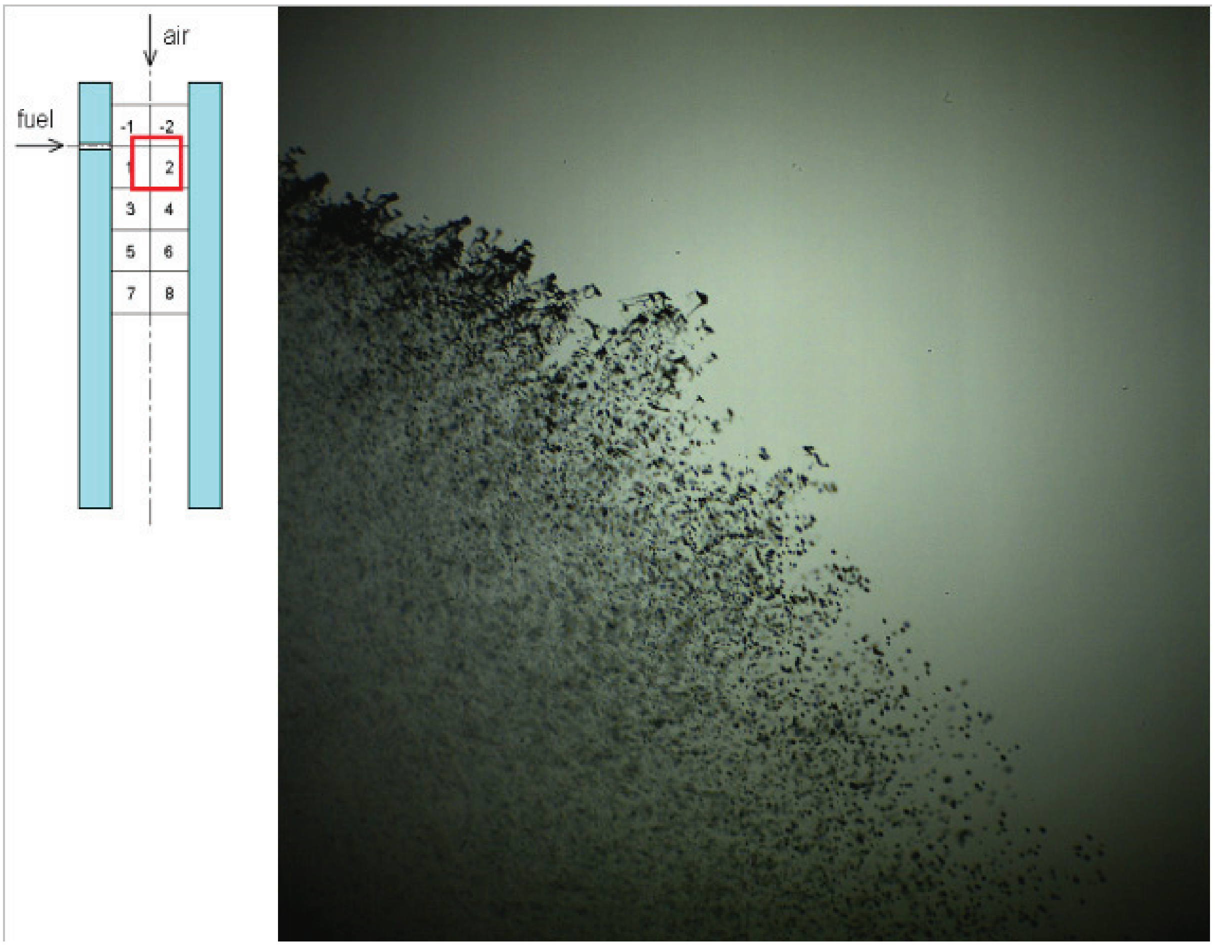

Fig. 5. Experiment No. 16 – frame recorded by high-speed camera (frame 1403)

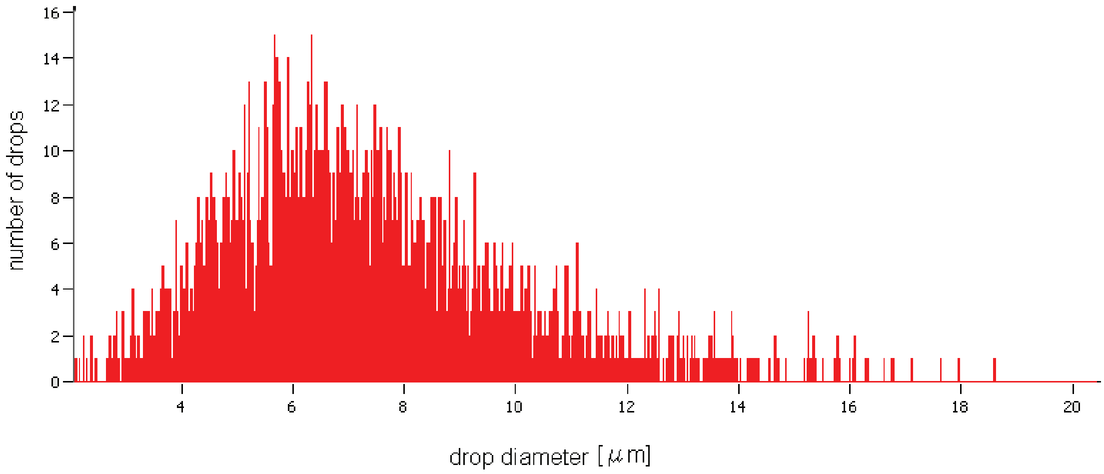

Fig. 6. Experiment No. 16 (Frame 1403) – droplet diameter histogram

6. Summary

1. Initially applied visualization method using a high-speed camera equipped with a special lens for microphotography gives a satisfactory quantitative image of the investigated injection process. It permits to measure the individual droplets of kerosene even little as 1 µm of diameter. A partial picture of the process (the area of about 6 x 6 mm) and time-consuming processing of frames (several hours per frame) should be considered for inconvenience.

2. Applying of a simplified mathematical model of injection makes possible reasonably proper prediction of average size of droplets and their trajectory in the air stream.
3. Performed experiments showed, that in case of stream-type injectors a large number of small injection holes in detonation chamber should be applied, in relation to disintegration of injected fuel as well as spatial uniformity of created combustible mixture.

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