Study of Rain Simulation for Aircraft Engine Certification

A I Guryanov, O A Evdokimov, S V Veretennikov, M M Guryanova and K L Kalinina

Department of general and technical physics, P.A. Soloviev Rybinsk State Aviation Technical University, Pushkinast.173a, Rybinsk, 152934, Russian Federation

E-mail: marialex2004@mail.ru

Abstract. Engine tests under flight conditions are extremely important at the stage of its complex debugging. These conditions include the simulation of icing, check for the penetration of birds in the inlet vanes, modeling hail and rain. Simulation of rain due to its significant unsteadiness need providing requirements for the concentration of water in the air, the distribution spectrum of droplets by size, the value of the average diameter of the droplets, the mass flow rate curves for the injectors and the conditions of interaction of droplets with air. This paper contains information about the developed method of calculating the characteristics of the injector for the necessary modes of water injection into the engine as well as experimental study of the injector and conducted studies of the parameters of its operation process, including the choice of optimal modes. As a result of the research, an injector was developed that allows to obtain the average median diameter of 2.66 mm and droplets of the certification spectrum. Also there was worked out the schematic diagram of the collector module of the installation for rain simulation that meets the certification requirements: simulation of rain in the "idle power" and "take-off" modes with the condition of simultaneous provision of water concentration in the air of 20 g/m³ and the average median diameter of 2.66 mm. This installation provides operation in transient modes with the condition of maintaining the water concentration in the air of 20 g/m³.

1. Introduction

A very important problem at the stage of aircraft engine debugging is its testing under flight conditions, in particular, the effect of rain. Water ingestion into engine typically has negative effect on its operation, as indicated by numerous studies of rain erosion of the compressor blades [1-4]. It leads to a decrease in performance and an increase in the risk of unstable oscillations [5, 6] as well as a high probability of problems associated with the flame blowout [7].

In order to organize the conditions corresponding to rain, it is necessary to take into account the unsteadiness of the phenomenon [8–11] and a significant number of large drops in the spectrum. Therefore, during the tests, an important condition is the formation of a spectrum of drops in the required range of diameters. It can be considered like an inverse problem when the geometry of the nozzle should be selected to provide the available parameters of the liquid at the nozzle’s outlet. The purpose of the work is to obtain a nozzle of such geometry, which will provide the necessary values of all operational parameters. This research will give a possibility to offer a scheme of collector for supplying water to the engine.

An important parameter of evaluating the effectiveness of nozzles for different purposes is the size of the drops [12–15]. When spraying fuel, the flame structure depends on the droplet spectrum [7], and when testing the engine, this factor affects the safety of future operation. Among all the methods of
spraying, the centrifugal one is quite widespread [16]. Possible application of this method is a drum-type nozzle. Liquid enters a rotating disk, on which, due to the action of centrifugal forces, it moves to the edge and breaks off from it in the form of bundles of drops, which are then separated [17]. This method of spraying allows to obtain droplets in a wide range of sizes, which is in good agreement with the research purpose. The transition between the operation modes is carried out mainly by changing the speed of rotation of the disk [18]. Increase in angular velocity defines decrease in the droplet diameter. A similar decrease in droplets occurs when the diameter of the rotating disk increases or when grooves are added [19, 20] Despite numerous studies, understanding of the characteristics of the droplets formed in this way is not enough. Generalization of the results of different studies and their expression in dimensionless form differs among different authors and is often inconsistent [21]. It does not allow considering the option of using this nozzle to create a rain simulation system. Another suitable option is the use of jet nozzles. Liquid jets form due to changes in differential pressure and then disintegrate into large droplets. Such nozzle is easier to adjust, as the spectrum can be changed controlling the flow rate and pressure difference. Also this method of droplets formation is less energy-consuming [22].

2. The basic requirements for installations of rain simulation
To simulate rain in a model setting, conditions are necessary that lead to multiple crushing of water jets supplied in the form of axisymmetric wave-like bundles or a thin veil from the injectors to the air flow at the entrance to the engine [22].

Averaged median droplet diameter is of $2.66 \times 10^{-3} \text{m}$. The top of $7.0 \times 10^{-3} \text{m}$ and the bottom of $0.5 \times 10^{-3} \text{m}$ borders of the distribution of droplets in size are presented in Figure 1 and caused by processes of coagulation and disruption, which occur when the motion of droplets is in the air flow [25]. The intensity of atmospheric rain, expressed in the form of water concentration in 1 m$^3$ of air in Figure 2, significantly depends on the height relative to the sea level [14, 23].

Water droplets of different size and size distribution than those shown in Figures 1 and 2 may be used if the replacement does not reduce the requirements for these tests.

![Figure 1. Standard size distribution of rain droplets [23].](image1)

![Figure 2. The standard atmospheric concentration of water in the air under rain conditions [23].](image2)

3. The results of calculation studies of the parameters of the rain simulation
The problem belongs to the class of inverse problems. To solve the problem, it is necessary to calculate the decay of the liquid jet in the air flow taking into account some factors, such as water mass flow under “idle power” and “take-off” modes, and the concentration of water ($20 \text{ g/m}^3$) in the atmosphere in accordance with the Aviation Requirements [23].

The formation time of a drop of median diameter of $2.66 \cdot 10^{-3} \text{ m}$ in compliance with equation (1) is $\tau = 0.0057 \text{ s}$. 


Taking into account the polydispersity of simulated rain, an integral time of droplets flight from the cross section of the liquid injection to air intake must be provided at the level of not less than $\tau = 0.0243$ s. This can be achieved at a distance of $R \geq 5$ m from the engine air intake.

The destruction of the boundaries of the droplet and its fragmentation into a set of smaller ones occur at values of Weber number $We \geq 10$. The range of values of $We$ number from 0 to 10 is valid for simulation of rain. When obtaining the dependence of the Weber number on the pressure difference in the nozzle, it is possible to specify the range of the pressure difference, which corresponds to favorable conditions excluding secondary destruction of the drops.

When finding the dependence of the Weber number on the pressure difference in the nozzle at different distances, it is necessary to use the air velocity corresponding to the distance for which the calculation is carried out. Water velocity has a power dependence on the pressure difference that allows to calculate this quantity. Under condition of 5m distance and air velocity of 37 m/s, on the mode of “idle power” the differential pressure at the injector $\Delta p = 2.51 \times 10^5$ Pa, for the operating mode "takeoff" $\Delta p = 10.85 \times 10^5$ Pa.

To define the number of nozzles, the continuity equation is used and the dependence of the mass flow through each nozzle on the pressure difference in the nozzle is obtained (Figure 3). The value of orifice coefficient was $\mu = 0.82$.

The number of nozzles is defined by the ratio of the total water flow to the flow through one nozzle. At the same time, the water flow rate has a linear dependence on the concentration of liquid in the air, which is 20 g/m³. Water mass flow through one nozzle is defined by the nozzle diameter and the pressure difference in the continuity and Bernoulli’s equations under the condition of water incompressibility.

The required number of nozzles included in the collector module for the "idle power" mode at the selected differential pressure $\Delta p = 2.51 \times 10^5$ Pa is $n = 14$, for the "take-off" mode at $\Delta p = 10.85 \times 10^5$ Pa was $n = 28$ (Figure 3). The total flow rate of water injected into the engine at intermediate modes of operation is provided by the serial connection of two independent pressure collectors, including 15 injectors each. Parameters of operating modes are accepted for Russian engine PD-14, the creation of which is at the stage of certification tests.

To describe the dynamics of changes in the pressure difference in the nozzle, it is necessary to know the flow rate for one nozzle and the total mass flow rate. When comparing all the equations mentioned above, the pressure difference function can be written in the form of equation (2), and shown in Figure 4.

$$\Delta p = \frac{G_{\text{water}}^2 \cdot 16}{n^2 \cdot \mu^2 \cdot \pi^2 \cdot d_{\text{noz}}^4 \cdot 2 \cdot 10^5 \cdot \rho_{\text{water}}}.$$  (2)
Figure 3. The dependence of water mass flow injected by one injector on differential pressure (1); The dependence of the required injectors on differential pressure (using the auxiliary vertical axis): 2 – "idle power"; 3 – "takeoff".

In the stationary mode “idle gas” simulation of rain is performed using the first collector operating at a pressure drop $\Delta p = 2.51 \times 10^5$ Pa (Figure 4). Up to the time $\tau = 7$ s, the dynamics of water flow through the collector is provided by increasing the pressure difference on the injectors’ nozzles from $2.51 \times 10^5$ Pa to $7.89 \times 10^5$ Pa (Figure 5), which causes an increase in liquid mass flow from 1.58 kg/s to 3.54 kg/s. At the time $\tau = 7$ s, the second collector is switched on and by the time $\tau = 8$ s at a pressure difference of $0.67 \times 10^5$ Pa, it adds 0.97 kg/s of water. In the time range from 8 s to 10 s, the pressure difference on the first collector increases from $7.89 \times 10^5$ Pa to $10.1 \times 10^5$ Pa, on the second collector – from $0.67 \times 10^5$ Pa to $10.1 \times 10^5$ Pa. Thus, by the time $\tau = 10$ s, both collectors are output to the same modes in terms of pressure difference and water flow, injecting 3.83 kg/s of liquid each into the engine. In the time interval from 10 s to 15 s, the pressure difference rises to a value corresponding to the “take-off” mode $\Delta p = 10.85 \times 10^5$ Pa on each of the collectors, determining the total water mass flow for both collectors of 7.89 kg/s.

Figure 4. Dynamics of change of pressure difference on nozzles of injectors on transient modes of operation of the engine: 1 – mass flow through the first collector; 2 – mass flow through the second collector.

Figure 5. The dependence of water mass flow injected into the engine on time: 1 – mass flow through the first collector; 2 – mass flow through the second collector; 3 – total mass flow.
4. The results of experimental studies of the injectors for rain simulation

Experimental study of nozzles was carried out by means of IPI method. The diameter is measured by the distance between the bands in the interference pattern formed by the reflected and once refracted light. The main components of the IPI method system are:

- Nd:YAG laser 532 nm;
- CCD camera 4 MP with optical amplifier unit;
- Measuring targets and Actual Flow software.

Droplet size measurement error was less than 5%. Distilled water with a temperature of 25 °C was used as a sprayed liquid. The value of the control section on which the indicators were set was equal 0.8 of the nozzle’s diameter.

To study the parameters of macro drop flow there were designed and created five experimental prototypes of injectors shown in Figure 6. The main differences between them are in the geometric characteristics of their nozzles.

One of the experimental prototypes (injector #2) at pressure difference of $2.35 \times 10^5$ Pa has the averaged median diameter of 2.644 mm, while the distribution spectrum of droplets in diameters has a maximum in the range from $2.5 \times 10^{-3}$ m to $3 \times 10^{-3}$ m. It should be noted that there are no droplets in the obtained spectrum with a diameter of more than $6 \times 10^{-3}$ m (Figure 7).

The averaged median diameter is significantly affected by the size of the transverse slit in the injector’s nozzle. It is proved by the comparison of the results of the study of injectors #2 and #3, as well as #4 and #5 (Figure 8). The check by the Weber number $We$ showed that the condition for obtaining the averaged median diameter of the droplets around the value of $2.66 \times 10^{-3}$ m under the condition $We \leq 10$ is satisfied only by the nozzle #2 (Figure 9).

![Figure 6. Experimental prototypes of injectors.](image6.png)

![Figure 7. Droplet diameter distribution (experimental prototype #2) at pressure difference $\Delta p = 2.35 \times 10^5$ Pa).](image7.png)

| Table 1. Geometric characteristics of injectors’ nozzles. |
|----------------------------------------------------------|
| Number of prototype | Diameter of the central nozzle $d_c$, $10^{-3}$ m | Width of the transverse slit $b$, $10^{-3}$ m | Depth of the transverse slit $h$, $10^{-3}$ m | Shape of the transverse slit |
|---------------------|---------------------------------------------|------------------------|--------------------------|---------------------------|
| 1                   | 4                                           | 2.5                    | 2.5                      | Cylindrical               |
| 2                   | 3                                           | 3                      | 3                        | Rectangular               |
| 3                   | 3                                           | 2                      | 2                        | Cylindrical               |
| 4                   | 2.5                                         | 1.5                    | 5                        | Rectangular               |
| 5                   | 2.5                                         | 1.5                    | 2.5                      | Rectangular               |
The refinement of the injectors allowed to obtain a version that provides an average median diameter of 2.662×10⁻³ m and a range of diameters of the macrodrop flow corresponding to the certification spectrum from 0.5x10⁻³ m to 7x10⁻³ m at pressure difference Δp = 2.35×10⁵ Pa. This corresponds to the water pressure at the inlet of the injector of 3.363×10⁵ Pa under conditions of its discharge to the standard atmosphere.

The collector module consists of two independent collectors in the form of polygonal ring pipes (d = 0.1 m) with radial branches (d = 0.04 m). Collectors contain 15 nozzles each (Figure 10). Simulation of rain can be carried out on the “idle power” and “take-off” modes with the condition of simultaneous provision of water concentration in the air of 0.02 kg/m³ and the averaged median diameter of droplets 2.66×10⁻³ m as well as operation on the transitional modes between “idle power” and “take-off” under the condition of maintaining the water concentration in the air of 0.02 kg/m³.

Figure 8. The dependence of the averaged median diameter of droplets on pressure difference: 1 – prototype #1; 2 – prototype #2; 3 – prototype #3; 4 – prototype #4; 5 – prototype #5.

Figure 9. The dependence of the averaged median diameter of droplets on Weber number: 1 – prototype #1; 2 – prototype #2; 3 – prototype #3; 4 – prototype #4; 5 – prototype #5.

Figure 10. Scheme of the collector module.
Conclusion
The paper presents the results of the experimental study of nozzles for rain simulation for the certification of aircraft engines. The spectrum of the formed drops corresponds to the certification one and has a mean median diameter of $2.66 \times 10^{-3}$ m. The operation limits for the water pressure at the injector’s inlet range from 0.1 MPa to 1.8 MPa. The required value of the median diameter of the droplets $2.66 \times 10^{-3}$ m is provided by the pressure difference on the nozzle $\Delta p = 2.35 \times 10^5$ Pa. On the basis of experimental studies, a scheme of the collector module is proposed and the main operating modes of the installation in connection with the characteristics of the aircraft engine are calculated. Change in the differential pressure from the value $\Delta p = 2.51 \times 10^5$ Pa on the mode "idle power" to the value $\Delta p = 10.81 \times 10^5$ Pa on the "take-off" mode leads to increase in total water mass flow from 1.58 kg/s to 7.89 kg/s, providing a constant value of the water concentration of 20 g/m$^3$ for mentioned modes.

References
[1] Liersch J and Michael J 2014 J. Phys.: Conf. Ser. 524 012023
[2] Hamed A, Tabakoff W C and Wenglarz R V 2006 J. Propuls. Power 22 350
[3] Ghenaiet A, Elder R L and Tan S C 2001 ASME Turbo Expo 2001-GT-0497
[4] Ma D, Harvey T J, Wellman R G and Wood R J 2019 Wear 426-427 539
[5] Sayma A I, Kim M and Smith N H S 2003 J. Propul. Power 19 517
[6] Cheng P, Li Q and Chen H 2019 Acta Astronautica 154 61
[7] Burson-Thomas C B, Wellman R G, Harvey T J and Wood R J 2019 Wear 426-427 507
[8] EASA 2007 Certification Specifications for Engines CS-E 790 Ingestion of Rain and Hail
[9] Roumeliotis I, Alexiou A, Aretakis N, Sieros G and Mathioudakis K 2014 Journal of Engineering for Gas Turbines and Power 137 (4) 041202
[10] Garipov M D and Sakulin R Yu 2011 Russian Aeronautics (Iz VUZ) 54 (3) 264
[11] Valentine J and Decker R 1995 Journal of Aircraft 32 (1) 100
[12] Santangelo P E 2010 Exp. Therm Fluid Sci. 34 (8) 1353
[13] Bian J, Zhang D, Sun R, Wu Y, Tian W, Su G H and Qiu S 2019 Nuclear Engineering and Design 350 158
[14] Chen H, Li Q and Cheng P 2019 Acta Astronautica 162 424
[15] Chen Z, He Z, Shang W, Duan L, Zhou H, Guo G and Guan W 2018 Fuel 232 562
[16] Li Y, Sisoev G M and Shikhmurzaev Y D 2018 Phys. Fluids 30 092101-1-20
[17] Sungkhaphaitoon P, Plookphol T and Wisuttmethangoon S 2012 Int. J. Appl. Phys. Math. 2 77
[18] Ahmed M and Youssef M S 2014 Chem. Eng. Sci. 18 107
[19] Kuhnhenm M, Luh M F, Joensen T V, Reck M, Roisman I V and Tropea C 2018 Expt. Fluids 59 (117) 1
[20] Peng H, Shan X, Ling X, Wang D and Li J 2018 Appl. Thermal Eng. 128 1565
[21] Kumar P and Sarkar S 2019 Chemical Engineering Research and Design 145 76
[22] Guryanov A I and Kalinina K L 2018 MAI Journal 25 (1) 18
[23] Aviation rules AP-33 2004 Airworthiness standards aircraft engines (Moscow: Aviaizdat)
[24] ICAO 2015 Aviation security oversight manual (Doc 10047)
[25] Airworthiness Directive No.: 2017-0144 2017 Ice and Rain Protection