Experimental study of cleaning aircraft GTE fuel injectors using a vortex ejector

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Abstract. The main ways of cleaning the fuel injectors and the circuits of jet and vortex ejectors used for pumping gas, liquid and two-phase media, as well as for evacuation of enclosed spaces are analyzed. The possibility of organizing the process of pumping the liquid out of the fuel injection manifold secondary circuit using a vortex ejector is shown experimentally. The regimes of manifold evacuation at various inlet liquid pressure values are studied. The technology of carbon cleaning fuel injectors using a washing liquid at various working process parameters is tested.

1. Introduction
While operating the aircraft gas turbine engines, many problems related to the deterioration of the quality of fuel spraying by injectors due to their coking arise. At present, the carbon cleaning of fuel injectors is carried out mechanically, which lies in their disassembling during the aircraft engine removal, which is quite costly and inefficient.

Hydraulic study of cleaning D-30KU/KP-KU-154 engines duplex fuel injectors (Fig. 1), conducted by JSC NPO Saturn earlier [1], has shown that the washing liquid supply through the primary circuit manifold and pumping out of the secondary circuit manifold is quite promising. This, on the one hand, allows to clean the injectors directly “over the wing” without disassembling them. On the other hand, it requires the hydraulic circulation circuit to be developed and implemented, that would provide the required pressure drops within the fuel injection manifold circuits. The scheme of the circulation process is shown in Fig. 2.

The problem above can be solved if the necessary pressure drop is provided through the creation of a rarefaction area at the fuel injection manifold secondary circuit inlet. Pumping the contaminated liquid out according to the circuit above is usually additionally accompanied by air masses sucking and requires the separation and filtration processes to be implemented for the purpose of its reuse organization.
2. Problem Statement

Analytical and numerical calculations of the liquid flow in the flow section of D-30KU/KP/KU-154 engines fuel manifold and injectors show that in order to organize their evacuation the absolute pressure within the range of 0.02–0.05 MPa is to be provided. Jet ejectors, despite their reasonable study and successful application in many industries, as a rule, cannot provide a sufficient evacuation level, and moreover, have large mass-dimensional characteristics [2-4].

![Figure 1. Design of the fuel injector](image1)

![Figure 2. Scheme of the washing liquid circulation](image2)

One of the possible solutions to the problem of cleaning the duplex fuel injectors within the manifold is the organization of a circulation cleaning, which includes the following: a heated washing liquid is supplied to the primary circuit channel, which is connected to the central jet nozzle of the injector.

Based on the parameters required for the liquid pumping out, a vortex direct-flow ejector with a 15 mm diameter mixing chamber diameter was designed, the exterior of which is shown in Fig. 3.

![Figure 3. Vortex direct-flow ejector](image3)

To experimentally study the evacuation of the fuel manifold using a vortex ejector, a test stand has been designed and installed, the functional diagram of which is shown in Fig. 4.
The test stand is operated as follows. The liquid is supplied to clean the fuel injection manifold 2, installed in the spraying tank 1. The required liquid supply parameters are provided by the feed circulating pump 13, transferring the liquid from the supply tank 11. Bypass pipeline flow valve 15 provides a stable pump operation. The fluid supply to the fuel injection manifold is controlled by flow valve 16.

The stand includes a receiving tank 4, the upper part of which consists of an inlet for receiving the mixture from the fuel injection manifold, a tap for measuring the tank pressure, and an outlet for intaking the separated gas phase using a vortex ejector 3. The washing liquid separated from the gas phase is taken through two lower openings by the pump 5.

The pump 13 is used to pump the washing liquid into the fuel injection manifold primary circuit, sucked at the outlet through the secondary circuit into the receiving tank 4 due to organizing the tank evacuation by a vortex ejector 3. The gas and liquid components are separated inside the receiving tank, and the gas component is sucked from the tank by a vortex ejector 3 mounted on its lid, thus creating a vacuum inside the tank. The liquid phase, which is a contaminated washing liquid, is pumped by the pump 5 through the lower tank openings and supplied to the filter for cleaning. In addition, the receiving tank is also used as a surge tank, allowing to ensure a uniform vacuum inside the fuel injector secondary circuit.

The compressed air from the compressor main line is supplied through the vortex ejector nozzle, performing the function of an active ejecting flow. The compressed air temperature, flow rate and pressure are monitored at the inlet of the ejector discharge nozzle.

The required flow rate ratio is regulated by the flow characteristics of the intake circulating pump 5, the control valve 8 installed on the return pipe and the shutoff valve 6. Bypass pipeline flow control valve 7 is installed for smooth control of the flow characteristics of the intake circulating pump 5. Part of the liquid pumped by the pump 5 is supplied to a mechanical cleaning filter 10, which provides the
washing decontamination, removing particles greater than 5 µm. The amount of liquid supplied to the filter is regulated by valve 9 and is measured by a counter 12, which allows to determine the amount of washing liquid to be returned to the system. The return washing liquid is supplied to the supply tank 11, which ensures the feed circulating pump 13 stable operation and allows to compensate for the washing liquid loss during the system operation. The amount of washing liquid lost during the washing period is determined by the washing liquid level changing in the supply tank before and after washing.

3. Experimental Results
Preliminary tests of the vortex ejector not connected to the fuel manifold of the gas turbine engine have shown the possibility of ensuring the secondary circuit evacuation along with the organization of the two-phase flow return pumping.

The results of studies on ejecting of liquid supplied through the fuel injection manifold primary circuit showed that pumping out by a vortex ejector is a nonstationary pulsating process. This is expressed by pumping the liquid by an ejector in small portions and is illustrated in Fig. 5 as the time dependent evacuation pressure function.

The nonstationarity is characterized by a clear-cut periodicity with an average frequency of 1.15 Hz, which causes only 52 % of the total flow rate of fluid supplied to the fuel injection manifold primary circuit return to the test stand hydraulic network. It is necessary to note that the time dependence in Fig. 5 illustrates the periodic evacuation process generally, more detailed study of the pressure pulsations requires to increase a sample rate of the measurements but this was not the purpose of the current experiment.

The physics of the process under consideration is as follows. When the vortex ejector in the operating regime, during the fuel injection manifold evacuating to 0.82·10^5 Pa and further liquid supply at \( p_l = 0.5 \cdot 10^5 \) Pa pressure the latter is ejected and pumped through the main line connecting the manifold outlet to the ejector. After some time, during which the first portion of the liquid moves from the fuel injection manifold to the ejector inlet, the passive nozzle cross section is completely filled with water, which leads to the pumped up flow “blocking” and the vacuum drop in the main line. After the first portion of the liquid slipping into the ejector, the main line gets reevacuated and the subsequent portions of water are sucked, further repeating the process.

The main line vacuum pressure periodic change determines the pulsating operating regime of the fuel manifold injectors, characterized by successive liquid spraying and sucking stages, which ensures only 52 % of the water mass fraction returned to the system.

Figure 5. Time dependence of the absolute vacuum pressure at absolute air pressure at the ejector inlet \( p_a = 2.5 \cdot 10^5 \) Pa, and liquid supply pressure \( p_l = 0.5 \cdot 10^5 \) Pa

Figure 6. Absolute vacuum pressure dependence of the liquid mass fraction returned to the system: 1 – \( p_l = 0.5 \cdot 10^5 \) Pa; 2 – \( p_l = 1.0 \cdot 10^5 \) Pa; 3 – \( p_l = 1.9 \cdot 10^5 \) Pa
To eliminate the noted negative moments, the scheme of experimental studies organization was changed by installing the receiving tank 4 between the fuel manifold 2 and the vortex ejector 3. This led to the experimental evacuation of not only the fuel manifold secondary circuit, but of the receiving tank 4 as well, which allowed to additionally organize the two-phase mixture separation by mass forces within the receiving tank volume and practically completely eliminate the washing solution slipping into the vortex ejector flow section. In case of applying the fuel manifold evacuation and the two-phase flow separation schemes above at the injectors industrial cleaning stage, the washing liquid slipping into the evacuating device flow section and potential loss shall be regulated by using the liquid pump to control the level of liquid inside the receiving tank and organizing the counterflow motion scheme for the air inside the receiving tank. When organizing the operating conditions corresponding to the temperature of the washing liquid close to the evaporation temperature, with the possible occurrence of cavitation along the test stand return line and fine dispersion within the receiving container, a simple condensing-type heat exchanger installation is reasonable.

The stated system optimization also allowed to completely eliminate the pulsating regimes of vortex ejector operation. The experimental results of the fuel injection manifold evacuation at various liquid supply pressure values are shown in Fig. 6.

It can be seen that the manifold evacuation to a pressure of \(0.8 \cdot 10^5\) Pa at a water supply pressure of \(p_l = 0.55 \cdot 10^5\) Pa allows to pumping out more than 96% of the liquid from the total mass supplied to the manifold. At evacuation pressure \(p_{vac} = 0.6 \cdot 10^5\) Pa for both fluid flow regimes above, the fraction of the liquid returned to the system exceeds 0.84. On the basis of the above, it can be concluded that, within the framework of the experimental scheme proposed for organizing the evacuation and separation of a two-phase flow, the only practical criterion for selecting an evacuating device (ejector, vacuum pump, etc.) is the possibility of providing the required evacuation level values.

Fig. 7 shows the photos of the fluid pumping by a vortex ejector in various operating regimes. It can be seen that with the absolute vacuum pressure \(p_{vac} = 0.95 \cdot 10^5\) Pa (Fig. 7a) some spray jets begin to shift to the periphery, contributing to an increase in the opening angle, but no liquid ejected into main line of the fuel injection manifold secondary circuit.

An increase in the evacuation pressure to \(p_{vac} = 0.9 \cdot 10^5\) Pa (Fig. 7b) facilitates the initiation of liquid pumping by the ejector, and the mass fraction of the water returned is \(g_{return} = 0.04\). The subsequent very insignificant increase in the evacuation pressure leads to a significant increase of \(g_{return}\).

The observed behavior of the function \(g_{return} = f(p_{vac})\) is due not only to an increase in the evacuation pressure. Fig. 7 clearly shows that a quasi-stationary liquid layer is formed in the injector nozzle area, bounded by the walls on the sides, and by the counter-ejected air from the bottom. It is obvious that a sufficiently large influence on the formation and retention of such a layer is exerted by the air-side surface tension forces, as well as by the adhesion forces of the injector nozzle side surfaces.

![Figure 7](image_url)

**Figure 7.** Visualizing the injector nozzle evacuation at \(p_l = 0.55 \cdot 10^5\) Pa: a) \(p_{vac} = 0.95 \cdot 10^5\) Pa; b) \(p_{vac} = 0.9 \cdot 10^5\) Pa; c) \(p_{vac} = 0.8 \cdot 10^5\) Pa
The conducted fuel injectors washing tests, both individually and as part of the manifold, demonstrated the high quality of spray nozzles exterior cleaning from varnish and carbon deposits (Figure 8). It is shown in Fig. 8 for two different injectors.

The development of various washing regimes in terms of liquid flow and pressure, vacuum pressure with kerosene spillage tests allowed to conclude that the nozzles operation requirements are complied with a wash time of at least 90 minutes. This is associated with the need for long-term softening and removal of surface deposits from the channels of the primary and secondary circuits, filters and spray nozzles.

![Figure 8. Photos of injector nozzles: a) injector 1 before cleaning; b) injector 1 after cleaning without circulating washing liquid; c) injector 2 before cleaning; d) injector 2 after cleaning with circulating washing liquid](image)

4. Conclusion
The conducted fuel manifold injectors evacuation and washing tests determined the possibility of up to 99% of the liquid mass fraction returned to the system and demonstrated the high quality of spray nozzles exterior cleaning from varnish and carbon deposits.

Acknowledgments
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