Unsteady effects at designing of modern aircraft jet engines

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Abstract. The operating conditions of advanced aircraft engines powered by cryogenic fuel analyze in the paper. The authors demonstrate cryogenic fuel supply systems must be designed with transients’ processes consideration. These processes based on significant changes in heat exchange and hydrodynamics in unsteady conditions. Unsteady conditions result to dramatic up to 3 times and more growth of heat exchange coefficient and hydraulic resistance. The authors suggested a methods can be used for unsteady processes in cryogenic fuel system calculation.

1. Introduction
An aviation transport efficiency is probably overly sensitive to traditional hydrocarbon fuels rising prices. This dependence is associated with a significant fuel component in the air transportation cost. The aircraft jet engines designers have been trying to switch to alternative fuels for more than 20 years.
Among alternative fuels for aircraft engines, cryogenic aviation fuels were considered. There are liquid natural gas which consists mainly of methane, liquid hydrogen and cryogenic propane. Cryogenic fuels for aviation have significant features compared to traditional fuels based on hydrocarbons. Cryogenic fuels have a higher cooling capability and efficiency before burning, as well as a higher calorific value than aviation kerosene (Table 1).

Table 1. Main fuels properties

|          | Density (kg/m³) at temperature (K) | Calorific value (MJ/kg) | Energy intensity (MJ/m³) | Cooling capability (kJ/kg) | Gas constant (J/kgK) | Liquid phase range (K) at pressure 0.1 MPa |
|----------|-----------------------------------|-------------------------|--------------------------|----------------------------|----------------------|------------------------------------------|
| Kerosene | 778.6/288                         | 43.5                    | 33855                    | 1330                       | 57.42                | operational                             |
| Liquid natural gas | 424.7/111                     | 50.0                    | 21100                    | 2830                       | 518.26               | 91…111                                  |
| Hydrogen | 71.5/20                            | 120.0                   | 8450                     | 13030                      | 4124.42              | 14…20                                   |
| Propane  | 580.0/230                          | 45.9                    | 26620                    | 3180                       | 115.24               | 85…230                                  |
In addition, cryogenic fuel is more suitable in terms of compliance with environmental requirements. For example, when using liquid methane, which will be used as fuel in this study, there are no emissions of lead and sulphur. Such fuel is a direct competitor to aviation kerosene from the ecology point of view.

In 1998, the Soviet Union tested an aircraft with a liquid hydrogen engine (Tu-155), and in 1989 began research and testing of aircraft functioning on liquid natural gas (Tu-156).

2. Methodology

Rocket and space cryogenic fuel systems have significant differences from the aviation cryogenic fuel system. During the first tests of the aircraft with hydrogen fuel, the hydrogen was in a supercooled phase (temperature up to -253°C) with an inert gas supercharged into the fuel tank. In contrast of hydrogen, liquid natural gas was located on the saturation line and did not require additional equipment to maintain it in a liquid phase, which was a significant advantage. Subsequently, several liquid natural gas-powered aircraft projects were developed, but they could not be implemented due to objective reasons.

Consider the scheme of the aircraft's cryogenic fuel systems (figure 1). The main elements of the cryogenic fuel systems are: a cryogenic fuel tank, an in-tank booster pump, cryogenic lines, a turbopump unit and a gasifier heat exchanger.

![Figure 1. Diagram of a cryogenic fuel system.](image)

1 - a cryogenic fuel tank, 2 - an in-tank booster pump, 3 - cryogenic lines, 4 - a turbopump unit, 5 - a gasifier heat exchanger, 6 – safety valve and 7 – regulation valve.

A mathematical model of a cryogenic fuel system was developed. The model allows to conduct computational and theoretical studies on the formation of the preliminary appearance of the cryogenic fuel system, and also allows to identify the features of its elements and to make recommendations on the organization of its operating modes. Mathematical model of the fuel system is a set of mathematical models of fuel system units that allows to determine the values of pressure, temperature, and hydraulic losses at all points of the fuel system.

The process of the preliminary technical appearance of the cryogenic fuel systems creation consists of the fuel system elements geometric dimensions calculation, the weight of the fuel system, etc. under the ensuring the operability of all the fuel system elements and the jet engine.

The cryogenic fuel system is created under the conditions of a certain flight cycle (figure 2). The flight cycle defines the engine operates mode corresponding to a certain fuel consumption. Changing one engine mode to another is transition process, which are often significantly unsteady. The unsteady
phenomena can lead to various kinds of unsteady heat transfer and hydraulic effects in the cryogenic fuel system.

Figure 2. Flight cycle. A – taxing before flight, fuel consumption ~ 0.0 kg/s; B – take off, fuel consumption 0.8 kg/s; C – cruise flight, fuel consumption 0.526 kg/s; D – descending, fuel consumption 0.2 kg/s; E – taxing after flight, fuel consumption ~ 0.0 kg/s.

The methane fuel has parameters on the saturation line. That is a reason it’s extremely sensitive to thermodynamic conditions during fuel transportation via the cryogenic fuel system to the jet engine. The engine operating mode changes at the points between different flight cycle stages. Each engine operating mode changes directly corresponds with the mass fuel consumption. In these cases, there are transition processes take place, and they are definitive unsteady. Heat transfer processes in unsteady conditions can entail significant escalation of heat transfer and hydraulic resistance. Such escalation of heat transfer can lead to liquid methane boiling. The boiling is absolute unacceptable for the stable turbopump unit operation. Booster pump is designed for a continuous fuel turbopump supply. The liquid methane boiling comes to the saturated vapor pressure in the pipeline increase and then comes to fuel heating. In the result, the reduction of the turbopump positive suction head and required booster pump pressure increase. A sharp pressure drop due to unsteady effects of hydraulic resistances can also leads to stability loss in the turbopump operation, and even to its complete shutdown.

In previous works, we have discussed the influence of unsteady conditions on thermal and hydrodynamic processes should be analysed [1, 2]. This thesis is a consequence of a heat transfer coefficients and hydraulic resistance in unsteady conditions significant change. When we talk about such changes in heat processes, we mean deviations of actual values from the values calculated by quasi-steady approach of more than 100% [1]. Obviously, such short-term changes in heat transfer and hydraulic resistance when developing aviation and space technology should be taken into account.

The fundamental causes of unsteady should be researched at hydrodynamic unsteady processes considering. Moscow Aviation Institute has a scientific school of unsteady processes since the 80's. The research is focused on the structural changes in unsteady turbulent flows study [3-8]. Previous researches have shown the main reason for in heat transfer and hydrodynamics deviation in unsteady conditions is a turbulent flow structure change [9, 10].

The analysis of experimental turbulent flows structure data [6, 11, 12] confirms a significant change in the flow structure near the channel wall. These changes undoubtedly effect on the turbulent flow macro-processes.

In previous work [1] turbulent flow in cross-section was segmented into several zones: zone viscous sublayer 0<η<5, zone of vortex structures generation 5<η<15, zone of vertexes structures interaction 15<η<30 and area η<30. Where η - dimensionless distance from a wall:

$$\eta = \frac{U_* y}{\nu}$$  \hspace{1cm} (1)

where $U_*$ – dynamic velocity, Pa·s; $y$ – distance from a wall, m; $\nu$ – kinematic viscosity, m$^2$/s.
where $\xi$ - hydraulic resistance coefficient; $\bar{U}$ - average axial velocity, m/s.

So, in isothermal conditions in a viscous sublayer $0<\eta<5$, the flow is not laminar. This zone is periodically under the influence of pulsations coming from zone $5<\eta<15$. These pulsations represent large volumes of medium with negligible oscillation amplitudes [1]. The interaction of these pulsations viscous sublayer comes to the generation in area $5<\eta<15$ vortex structures. New vortices move to the next area $15<\eta<30$, where there is an active vertexes structures interaction with the main flow. And outside area $\eta=70$ such vortex structures are no longer. This thesis also confirmed with recent research [13, 14]. In the near-wall area, the emission and movement of the vortex structure causes a local flow deceleration with a thickness of $15<\eta<30$ and a slight velocity gradient. At the same time the main stream has enough large mass and speed comparable to an average speed of layer currents. The interaction of these two structures – areas of slow flow and the main flow comes to intense ejection of vortices that form the basis of turbulent fluctuations [1].

Under conditions of accelerated flow, the axial velocity profile becomes more filled. This is evidenced not only by the results of research in Moscow Aviation Institute [8], but also by experimental data from other authors [11, 12]. The effect of "filling" the speed profile leads to "compression" of the near wall zone, which ultimately turbulent emissions intensifies. These processes lead to a significant increase in turbulent viscosity and turbulent thermal conductivity. This eventually leads to heat transfer and resistance increase during flow acceleration.

In condition of flow deceleration, the opposite structure processes is observed. The velocity profile becomes less filled [8, 11, 12]. The intensity of turbulent generation decreases. As a result, this comes to turbulent viscosity coefficient and turbulent thermal conductivity coefficient decrease. And, consequently, flow deceleration comes to heat exchange and resistance decrease.

The criterion of hydrodynamic unsteadiness was presented by authors [8] for estimating of hydraulic unsteadiness influence $Kg^*$. 

$$K_g^* = \frac{1}{\partial \tau} \left( \frac{\partial G}{G} \right)$$

where $\frac{\partial G}{G}$ - flow rate change, kg/s; $G$ - flow rate, kg/s; $d$ - internal channel diameter, m; $g$ - gravity constant, m/s².

Based on previous research a model of the unsteady conditions influence on heat exchange and hydrodynamics of turbulent flows was created. In practice, so-called quasi-steady approach is often used. Quasi-steady approach constitute a method when heat transfer and hydrodynamics in unsteady conditions are calculated via instantaneous flow parameters based on steady models. The comparison of unsteady and quasi-steady approaches heat transfer coefficient calculation presented in figure 3. The results of dimensionless heat transfer coefficient in unsteady process presented for the case $Re=3100...9300$, $Kg^* = 0...0.111$ and temperature coefficient $T_w/T_f = 1...1.18$. Parameter $Ho$ is the dimensionless time of unsteady process. The difference between unsteady and quasi-steady approaches reaches two times [1].
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Figure 3. Comparison of unsteady and quasi-steady approaches of heat transfer coefficient calculation; Re=3100...9300, Tw/Tf=1.18: a - quasi-steady approaches, b - unsteady calculation by V. Kraev’s model [1].

The results for hydraulic resistance coefficient during flow acceleration presented in figure 4. The graphs demonstrate difference between quasi-steady approach, calculations by experimental models of S. Markov, models of A. Nikiforov and S. Gerasimov [12] and V. Kraev’s model [1].

Figure 4. Flow acceleration influence on hydraulic resistance coefficient (Re = 6200 - 18700, Tw/Tf =1): 1 – quasi-steady approach, 2 - experimental model of S. Markov [11], 3 - model of A. Nikiforov and S. Gerasimov [12] and 4 - V. Kraev’s model [1].

Presented in figures 3 and 4 heat transfer and hydrodynamics coefficients data demonstrate a significant difference between experimental data and quasi-steady approach. These figures prove our thesis about that cryogenic fuel system calculations should be done only with unsteady effects consideration.

3. Results

The unsteady approach allows to take into account unsteady effects by optimizing parameters of cryogenic fuel system on designing stage and increase the reliability of the system totally.

The effect of cryogenic fuel flow acceleration at engine operating from “taxing” to "take-off" mode change done.

The heat transfer and hydraulic resistance coefficients data calculated according to the V. Kraev’s model [1] presented in figures 5 and 6. The dimensionless form of graphs shows the difference
between accelerated and non-accelerated flow. The horizontal axis is the time when the unsteady process occurs. Each line corresponds to a specific channel diameter.

![Figure 5](image1.png)

**Figure 5.** The fuel flow acceleration influence on the heat transfer coefficient for cryogenic fuel system for channel diameters: 1 – 50 mm, 2 – 30 mm, 3 – 10 mm and 4 – 5 mm.

![Figure 6](image2.png)

**Figure 6.** The fuel flow acceleration influence on the hydraulic resistance coefficient for cryogenic fuel system for channel diameters: 1 – 50 mm, 2 – 30 mm, 3 – 10 mm and 4 – 5 mm.

The calculations presented above shows that the unsteady process duration plays predominant role. It means, the faster unsteady process has the greater the unsteady effect influence. The diameter of channel, i.e. pipelines also play an important role. The higher unsteady effect corresponds to larger pipelines diameter.

Thus, the reduction of unsteady effects in cryogenic pipelines is possible by optimizing the pipeline diameter values or by increasing the unsteady process time.

The shut-off and control valves response time in cryogenic fuel system has a range of 0.8...10 seconds. The calculation and experimental data (figures 5 and 6) demonstrate, if the unsteady process is 5 seconds or more, the hydrodynamic unsteady can be ignored. However, for more rapid unsteady processes other methods should be used to reduce the unsteady impact. As we have already mentioned above, unsteady effects can come to liquid methane boiling and a decrease the turbopump positive suction head. An increase of the heat transfer coefficient more than 2 times, and an increase of the
Hydraulic resistance coefficient more than 3 times are unacceptable for cryogenic fuel system operating conditions. Based on the present research, cryogenic fuel system pipelines with the smallest diameter should be used. Thus, with a pipeline diameter of 5 mm, the unsteady effect of heat transfer with a process time of 1 second is limited to 25-30%. In case a such technical solution is not acceptable, the booster pump with a significant power capacity should be used.

Conclusion
Unsteady hydrodynamic processes take an important place in the cryogenic fuel systems transition operation. The results demonstrate a significant heat transfer coefficient and hydraulic resistance increase at the engine take-off regime. The reason for this is the turbulent flow structure fundamental change at hydrodynamically unsteady conditions. The authors identified heat transfer coefficient may exceed their quasi-steady values by more than two times, and the hydraulic resistance coefficient by more than three times. This difference can come to significant disruptions in the entire cryogenic fuel system, and may lead to operation failures. The results of calculations show the limits of quasi-steady approach applicability. Two parameters were observed – fuel valve response time and fuel pipelines diameter. The authors suggest to use pipelines of the smallest diameter and/or increasing the significant power capacity booster pumps in unsteady processes with duration less than 5 seconds.

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