Computational research of parameters of cryogenic propellant system for high-speed aircraft

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Abstract. Utilization of cryogenic fuels (condensed natural gas, liquid hydrogen or propane, etc) appears to be promising for aircraft engine. The urgency of switching to cryogenic fuels is due to their high heat of combustion, cooling capacity, environmental safety, significant natural reserves and low cost. The task of the work is modeling and thermal-hydraulic optimization of the cryogenic fuel system by reference to specific features of its use in the high-speed aircraft and in particular: long endurance, high heat-transfer intensity, variety of operation conditions, alternating G-loading, etc. To solve the presented scientific problem, the mathematical model and the parameters calculation procedure of cryogenic fuel system have been developed, which makes it possible to carry out parametric and optimization studies in a wide range of operational conditions. The work presents the results on the selection of cryogenic fuel system parameters for a advanced high-speed aircraft on cryogenic methane. The main mechanisms of the various factors influence on the fuel system mass characteristics and the losses by fuel gasification have been obtained.

1. Introduction

Fuel resources endowment is the key problem that determines the development of the economy and national security of the nation. The resent escalation in the price of petroleum did not reduce the trend of its rising consumption in the world, leading to depletion of its reserve in all countries in the first half of this century. Consequently, the challenging goal of the transition from petroleum to alternative fuels in transport and industry should be solved in short terms. Abovementioned issue is especially important for Russia due to its vast territory, rich natural resources, geographical location and a variety of climatic zones.

The problem of transition to alternative fuels is most noticeable in aviation, because of constantly growing transportation intensity. At the same time, the share of fuel consumption in aviation in the world is constantly increasing. Therefore, alternative aviation fuels applications are studied in developing countries due to lower cost and ecological benefits.

Alternative aviation fuels include cryogenic fuels: liquid hydrogen and liquefied natural gas (LNG) mainly composed of methane. The potential of these fuels can be assessed on the basis of below properties, namely high cooling capacity and energy content per unit mass that can significantly improve aircraft performance. Fuel system is one of the most important systems of the aircraft, and the cryogenic one in mainly respects differs from the aviation kerosene fuel system.
The Russian Federation has the priority in cryoplane development. First flights of Tu-155 aircraft proved principal feasibility of transport aircraft flying on liquid hydrogen on 15 of April 1988 and LNG on 18 of January 1989.

Problems with cryogenic fuels storage and transportation for ground vehicles are widely studied [1], but its utilization in aviation requires adaption. Cryogenic fuel systems for aerospace vehicles differ from aviation systems [1]. At the experimental Tu-155 flying laboratory liquid hydrogen was in a supercooled state supercharged with inert gas, and during the flights on LNG the fuel was in a phase equilibrium state. In both cases a cryogenic fuel tank was used with thermal blanket, fabricated by ground cryogenic engineering [2]. Afterward, several projects of aircraft on LNG have been developed, but they could not be completed for objective reasons [3]. Calculation and design methods of cryogenic fuel systems of aircraft are practically not described in the scientific and technical literature. In view of prospects of cryogenic fuels, particularly methane, the development of effective aviation cryogenic fuels and aircrafts on them is relevant in Russia and other countries. Design methods of cryogenic fuel systems are the integral part of the chemmotology analysis based on the modern continuous acquisition and lifecycle support (CALS) technologies, which allow significant reduction of scientific and project work [4].

Research activities in the field of heat and mass transfer in cryogenic fuel tanks of the rocket engineering are conducted worldwide. Issues related to cryogenic tanks icing, chilldown, fueling modes, stratification, thermostability, etc are resolving [5–8]. But the issue of cryogenic fuels utilization in aviation is not included to research. There is no interest in developing a long-range aircraft on cryogenic fuel in the world. The main cause of it is following: kerosene and biofuel are considered as a fuel in medium and long terms by American and European aviation engineers.

2. The design method of an aircraft cryogenic fuel system

In addition to cryogenic fuel tanks and pipelines with thermal insulation coating, the cryogenic fuel system includes a boost bled-impeller pump located in a fuel reservoir and a jet pump, figure 1. The boost bled-impeller pump is designed for continuous fuel supply to a turbopump assembly of the engine with the required mass-flow rate and positive suction head ensuring its reliable operation. The jet pump ensures a stable, cavitation-free operation of the boost bled-impeller pump by maintaining a predetermined liquid level in the fuel reservoir under all operating regimes.

Cryo-tank has a safety valve, through which the steam is released, when the maximum allowed pressure in the tank (in the terms of structural capability) is reached. The cryogenic fuel system parameters are considered optimal, if fuel loss through the safety valve (as a result of heating) is minimal during the operation. Moreover, the fuel system dimension and mass, including the unused fuel mass in the fuel reservoir, should also be minimal.

Taking into account that increase of heat insulation thickness is limited by design considerations, because of cryogenic fuel system dimension and mass rise, the most effective way of fuel heating rate abatement is to reduce the heat fluxes from the boost bled-impeller pump and the jet pump due to coastdown and performance increase.

The boost bled-impeller pump power is determined by its head and output, which includes “passive” (to the engine) and “active” (to the jet pump) outputs. Required head of the boost bled-impeller pump increases in proportion to sum of total pressure losses and pressure gain of fuel heavy vapor in the pipelines due to fuel heating. Studies show that it is possible to reduce abovementioned pressure sum (which determines TPA suction head reduction) with diameter and pipeline thermal insulation thickness optimization (figure 2). Moreover, the boost bled-impeller pump head reduction leads to an increase in its efficiency due to reduced leakage and friction losses [9].

It is an obvious point that it is possible to reduce the boost bled-impeller pump power only by decreasing of “active” output. This leads to jet pump power decrease [10]. Experiments show
Figure 1. Cryogenic fuel system schematic with two tanks: BP—boost bled-impeller pump; FR—fuel reservoir; JP—jet pump; TPA—turbopump assembly; SV—safety valve; CV—control valve.

Figure 2. An example of the calculation of maximum losses in the pipeline due to its diameter and thermal insulation thickness: \( \Delta p \)—pressure; \( d_{\text{opt}} \)—optimal pipeline diameter; \( d_{\text{p}} \)—pipeline diameter.

that at the take-off there is a decrease in the fuel level in the fuel reservoir, which intensifies with the jet pump power decrease and causes the cavitation performance of the boost bled-impeller pump. As a result, it is necessary either to increase the fuel reservoir volume (but at the same time the unused fuel mass grows) or to reduce the calculated suction head of the boost bled-impeller pump due to the efficiency lowering (the boost bled-impeller pump head
increase as its speed falls and the outer diameter of the centrifugal wheel increases), which is also undesirable. From this perspective, it becomes necessary to select the optimum ratio of the fuel reservoir volume, the jet pump power and calculated suction head of the boost bled-impeller pump, which give the minimum heat flux and the minimum unused fuel mass.

Thus, the aircraft cryogenic fuel system design goal is its thermal and hydraulic optimization in accordance with the mutual influence of all elements and operation features of aeronautical equipment, namely the parking and flight duration, variety of operation conditions, deceleration impact, etc.

When developing the mathematical model of heat exchange in the cryo-tank and pipelines the relations given in [11] were used. The computational scheme of heat exchange between the environment and fuel in the tank is shown in figure 3. The tank is conditionally divided into three regions in which heat exchange processes are different.

As an example heat transfer rate in region C is
\[ q = \frac{T_1 - T_2}{\frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2}}, \]
where \( T_1 \) and \( T_2 \) are the temperatures of air and cryogenic fuel, \( \alpha_1 \) and \( \alpha_2 \) are heat transfer coefficients of surrounding air and cryogenic fuel, \( \lambda \) is heat conduction coefficient of the wall with thickness \( \delta \).

Air around the fuel tank can be considered as confined space, therefore heat transfer coefficient \( \alpha_1 \) is calculated from equivalent heat conduction coefficient \( \lambda_e \)
\[ \alpha_1 = \frac{\lambda_e}{\Delta}, \]

Figure 3. Heat flow diagram.
where $\Delta$ is width of volume around the tank (from tank to aircraft fuselage). The value of $\lambda_e$ is formulated as

$$\lambda_e = \varepsilon_c/\lambda,$$  \hspace{1cm} (3)

where $\varepsilon_c$ is coefficient of convection, that shows the relation between real heat transfer and heat transfer by heat conductivity. This coefficient can be calculated empirically with known Grashof (Gr) and Prandtl (Pr) numbers as

$$\varepsilon_c = 0.18 \cdot (GrPr)^{0.25}. \hspace{1cm} (4)$$

The similar correlations may be used to calculate the heat transfer coefficient $\alpha_2$ in the tanks with relatively small diameter (less then 1.5 m). In region A, the heat flux is directed through the thermal insulation of the tank to the gaseous fuel above the liquid fuel. In region B, the heat flux flows from the gas phase of the fuel into the liquid phase, and in region C the heat flux is directed to the liquid fuel through the thermal insulation of the tank. The fuel flow in the pipeline is forced convection. The heat exchange process is calculated with regard of time, i.e. there is an iteration with a set time interval. At each time iteration heat transfer is calculated in all regions. The verification of the mathematical model of heat transfer in the cryogenic tank was carried out according to the experimental data obtained during full-scale testing of cryogenic fuel system. During the mathematical model verification and subsequent parametric studies the biggest calculation error was found to be the result of the inaccuracy in determining the thermal conductivity of thermal insulation material. Radiation heat exchange was calculated by known relations, taking into account the absorption and reflection of radiation \[11\]. Calculation of thermophysical properties of cryogenic fuels was carried out with the help of mathematical model from \[12\].

Calculation of flow friction in the pipelines in reliance on bends and in the valves was carried out using laws given in \[13\]. Moreover, the total pressure loss and the pressure gain of the heavy fuel vapors were determined in the wide range of flow operating parameters for the selected thermal insulation and the pipeline diameter (figure 4). Their sum determines the reduction of the TPA suction head in the pipeline, which is necessary for the calculation of the boost bled-impeller pump.

The geometry, energy and cavitation characteristics of pumps and also heat fluxes were determined \[9,10\]. At first, the boost bled-impeller pump with the lowest power was taken, and then the one with a fixed “passive” flow, iterative increasing its pressure. The calculation was carried out until the pressure ratio in the boost bled-impeller pump did not exceed the value of the TPA suction head reduction. Thereat, the oblique angle of the head-capacity curve of the boost bled-impeller pump was selected each time such that this excess was minimal throughout the entire range of its outputs (see figure 4).

The jet pump power starting from the minimum value was iteratively increased by the “active” fuel output increase, not until the available suction head of the boost bled-impeller pump, corresponding to the take-off regime, came to “critical” value. Thus, the described algorithm makes it possible to obtain the power-supply units parameters of cryogenic fuel system so that, with a minimum excess of pump power, a reliable fuel supply of the engine for each variant of the pipeline design is ensured.

The task of cryogenic fuel system optimization can be described by two criteria. The minimum mass of the cryogenic fuel system is a first criterion, and the second criterion is the minimum mass of the “discarded” fuel through the safety valve for the entire range of the mission. The array of the unimprovable data (Pareto optimal set) is the result of an optimization, which is the initial data for the analysis and the subsequent variant choice.

As an example the cryogenic fuel system of the advanced high-speed aircraft was analyzed. The variable data are as follows:
Figure 4. An example of the calculation of TPA suction head in the pipeline and the required pressure increase in the boost bled-impeller pump from fuel output: 1—the required pressure increase in the boost bled-impeller pump; 2—the TPA suction head in the pipeline; 3—the pressure loss in the pipeline; 4—heavy fuel vapors pressure at the end of the pipeline; $\Delta p$—pressure; $G_{\text{engine}}$—fuel mass flow rate.

- inside diameter of the pipeline;
- pipeline heat insulation thickness;
- tank heat insulation thickness.

The range of variation depends on layout and design features of the air frame.

The calculation is based on the flight cycle, performed by the advanced high-speed business aircraft, consisting of a turn around and rudder control before the take-off, routing and parking after the flight until the cryogenic refueling. The flight profile includes the following paths: take-off, height gain, cruise flight, push down, landing approach and touchdown.

Each path of the flight profile corresponds to the engine operation regime, which ensures the maintenance of thrust and, accordingly, the specified pitch attitude and flight velocity with appropriate fuel consumption. The aircraft parking (after refueling) before take-off is 2 hours, after landing (until the next refueling) is 2 hours.

The subject of research is the cryogenic fuel system composed of the two cryogenic cylindrical fuel tanks with spherical butt end (see figure 1). The diameter and length are different. The safety valve in both cryogenic fuel tanks meant for pressure drop 0.2 MPa. Both cryogenic fuel tanks are filled up to 95%. Thermal insulation material of tanks and pipelines is polyurethane foam.

3. Results

Pareto optimal sets of cryogenic fuel system parameters have been obtained for both cryogenic fuel tanks during the optimization research (figures 5 and 6).

Each point of Pareto sets corresponds to a certain set of optimal parameters of the cryogenic fuel system. Choice decision of a certain variant can be made depending on the priority of chosen
Figure 5. Solution set of optimal relative parameters for tank 1 of the cryogenic fuel system: $\bar{M}_D$—relative mass of “drawdown” of the fuel level; $\bar{M}_{CFS}$—relative mass of cryogenic fuel system; “O”—the point of Pareto sets with minimal fuel losses.

Figure 6. Solution set of optimal relative parameters for tank 2 of the cryogenic fuel system: $\bar{M}_D$—relative mass of “drawdown” of the fuel level; $\bar{M}_{CFS}$—relative mass of cryogenic fuel system; “O”—the point of Pareto sets with minimal fuel losses.

It is obvious that the most interesting parameters of the cryogenic fuel system during operation are those wherein fuel losses are absent or minimal (point “O” of Pareto sets) (see figures 5 and 6). Nevertheless, at take-off in the fuel reservoir there is a “drawdown” of the fuel level in case of the boost bled-impeller pump failure (during the regular take-off
Figure 7. Changes of pressure in the cryogenic fuel tank along the flight profile to the relative time of parking and flight: $p$—pressure; $\Delta p$—differential pressure for fuel “drawdown”; $\bar{t}$—the relative time of parking and flight.

two boost bled-impeller pump must function), which corresponds to the “critical” suction head of the boost bled-impeller pump (taking into account that only one boost bled-impeller pump provides fuel supply). The second tank is fuel losses critical during fuel bypass back through the safety valve as far as with the same amount of fuel losses its mass considerably exceeds the mass of the first tank (see figures 5 and 6).

Despite the same thickness of thermal insulation of both cryogenic fuel tanks, the intensity of LNG heating in them is different (figure 7), which is due to differences in their geometry. As noted above, the optimal design variant of the cryogenic fuel system is one in which there is no fuel discharge. But this is impossible to perform within the framework of the assigned task. However, the discharged fuel under these conditions can be diverted to the ground storage at an aerodrome rather than vent to atmosphere. The fuel vent to atmosphere is extremely undesirable, since methane is a greenhouse gas, and the fuel loss deteriorates the efficiency of the aircraft.

The end of the horizontal flight of the aircraft along an assigned route is an important path (see figure 7). At this moment, the pressure drop becomes minimal and fuel discharge is possible. Note that the two-criteria formulation of this optimization problem is preliminary when choosing the parameters of the cryogenic fuel system. In order to determine the characteristics and parameters of the cryogenic fuel system, optimization of the aircraft–engine–fuel system is necessary with respect to criteria of a higher level (flying range, fuel efficiency, etc). This is the goal of further research.

4. Conclusions
Developed mathematical models for cryogenic fuel system provided the opportunity to carry out the optimization and parametric research, which gave ground for following conclusions:

- Thermal insulation thickness, tank configuration and heat flux released during the booster pump operation have a significant influence upon the intensity of cryo-fuel heating. The
booster pump power depends on the length, diameter and thickness of the pipeline thermal insulation.

- Short-duration fuel “discharge” from cryogenic fuel tank through safety valve can occur at the end of cruise flight. If there are several cryogenic fuel tanks on the aircraft, then “discharge” is most likely from smaller tank. Therefore, the end of the cruise flight is the most critical.

- The parking time of the refueled aircraft is limited by cryogenic fuel tank, which has a smaller relative diameter, since higher intensity of heating of the cryo-fuel in it. It is reasonable to make greater thickness of thermal insulation for this tank. This increases the parking time of the refueled aircraft by 2–3 times, while the mass of the tank, respectively, will increase by only 0.3–0.7% of the aircraft weight.

- In accordance with variety of aviation cryogenic fuel systems operation conditions it is necessary to evaluate the pumps action and to select parameters that ensure their reliable operation in all possible regimes of the fuel system taking into account the change in fuel properties when heated in a fuel tank, pumps and pipelines. At the same time, it is necessary to take into account the influence of stratification, low-frequency oscillations propagated through the pipeline, heave of fuel surface, on the heat and mass transfer in the tank. It is also necessary to study the icing processes on the outer surfaces of the cryogenic fuel system of the aircraft.

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