Estimation of the mass of the centrifugal electric pump unit of the spacecraft thermal control system

Alexandr Bobkov1*

1Komsomolsk-Na-Amure State University, KnAGU, Department of Aircraft Engineering, 681013, Komsomolsk-on-Amur, Russia

Abstract. The article deals with the problem of estimating the mass of a centrifugal electric pump unit of a spacecraft thermal control system at the stage of preliminary design. The energy parameters of the electric pump are considered as the initial information relevant for the specified assessment: mass and volume flow \( \dot{V} \) (m\(^3\)/sec), head \( H \) (Joule/kg) and speed factor \( n_s \) (dimensionless parameter). Based on the known data, using a third-order equation, an approximation of the graphical dependence of the reduced mass \( m_r \) of aggregates on the mass flow rate of the coolant (kg/sec) was carried out. An analysis of the equation showed that starting from the value \( m = 0.15 \) kg/sec, the dependence becomes asymptotic, indicating the invariance of the reduced mass of the unit with a further increase in flow. The obtained dependence, covering a narrow range of variation, does not allow us to evaluate the changes of the reduced mass of the unit when designing a unified series of designs of the centrifugal electric pump unit of the spacecraft thermal control system, taking into account changes in such energy parameters as head, volume flow and speed coefficient. Therefore, at the 2nd stage of the study, an analysis of the influence of these parameters was carried out within the framework of the graph \( \dot{V} = f (H) \), containing the level lines \( n_s = \text{const} \) and \( m_r = \text{const} \). It follows from the graph that if the increase in pressure \( H \) is due to an increase in the number of revolutions of the rotor, then such a modification of the unit is not accompanied by an increase in the radial dimensions and absolute mass of the design of the centrifugal electric pump unit.

* Corresponding author: bobkov822@yandex.ru

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1 Introduction

The circulation of the coolant in the hydraulic circuit of the active thermal control system (TCS) of the spacecraft is provided by centrifugal electric pump units (CEPU) [1-7].

The degree of perfection of spacecraft systems is estimated by the specific power equal to the ratio of the system's power to its mass. For example, the specific power of the thermal control system of modern spacecraft lies in the range of 30–37 W/kg at a thermal power of 10 kW and a service life of 15 years [8-11]. The task was set to bring the degree of perfection of the TCS to values of 45...50 W/kg, with a service life of 25 - 35 years and a power of more than 20...30 kW.

1.1 Description of the design of the centrifugal electric pump unit

On Fig. 1 shows a cross-section of the unit, consisting of an impeller 1 and a DC electric motor, including an armature 2 and a sealed stator 3. When fixing the impeller 1 on the shaft of such an engine, it is not necessary to install an end seal and seal the cavities of the impeller and electric motor between themselves. Therefore, the cavity between the armature 2 and the stator 3 is filled with coolant (in Fig. 1 it is shaded in gray). The armature of the engine 2 is made in the form of a permanent magnet. Engine stator 3 is an outer housing with a package of active iron pressed into it. Screen 4 installed between armature 2 and stator 3 is made of non-magnetic stainless steel in the form of a cylinder hermetically connected to the motor casing. Screen 4 fits snugly against the inner surface of stator 3. Because of screen 4, the efficiency of the electric motor is lower due to additional losses in the screen and in the gap between armature 2 and stator 3. The gap can reach a value of the order of $0.8\cdot10^{-3}$ m, including screen thickness.

One of the directions for solving the problem is to increase the reduced mass of the centrifugal electric pump unit $M_M = M/\dot{m}$, where $M$ is the mass of the CEPU (kg), $\dot{m}$ is the mass flow rate of the coolant (kg/sec). In the pressure characteristics of CEPU, not mass, but volume flow $\dot{V}$ (m$^3$/s) is often used, the relationship between which is characterized by the formula $\dot{V} = \dot{m}/\rho$, where $\rho$ is the density of the coolant (kg/m$^3$).

The position sensor is located in the same housing with the electric motor, including the position sensor rotor 5 and the position sensor stator 6. The position sensor rotor 5 has the form of a segment (beveled cylinder) located on the same shaft with the engine. The segment performs the function of the signal element of the position sensor.
Sensing elements are located on the stator of the position sensor. Their number is equal to the number of motor windings, and the position corresponds to the position of the corresponding windings. Hall sensors, magnetic diodes, etc. can be used as sensitive elements. Under the influence of the signal element, they generate control signals entering the switch. The commutator is assembled from semiconductor elements and mounted in a separate box connected to the electric motor with a pin connector.

1.2 Hydraulic parameters of the centrifugal electric pump unit

The flow rate of the liquid coolant \( \dot{V} \) in the circulation circuit of the spacecraft thermal control systems, which provides the specified heat removal mode, is estimated by the dependence:

\[
\dot{V} = \frac{Q_m}{\rho \cdot c \cdot \Delta t}
\]

where \( Q_m \) - thermal load (W); \( c \) is the heat capacity of the coolant (Joule (kg·K)); \( \Delta t \) – heating of the coolant in the cooling path TCS (K).

The pressure loss \( p_{hr} \) due to the hydraulic resistance of the circulation path of the TCS spacecraft is due to two components:

\[
p_{hr} = \sum \Delta p_{hf} + \sum \Delta p_{lr} \tag{2}
\]

where \( \sum \Delta p_{hf} \) - hydraulic friction resistance on TCS spacecraft sections of the pipeline; \( \sum \Delta p_{lr} \) - pressure loss in local resistances.

The typical \( p_{hr} \) level of the circulation paths of the TCS spacecraft lies in the range of \( p_{hr} = (0.01...0.1) \) MPa [12-14].

2 Materials and methods

Low-flow centrifugal electric pump units TCS spacecraft with angular speed \( \omega = \pi n / 30 \) (sec\(^{-1}\)) in the range of values \( \omega = (400...1000) \) sec\(^{-1}\) and volumetric flow rate \( \dot{V} = 300 \times 10^{-3} \) m\(^3\)/sec belong to the class low-speed blade machines [5, 12]. At the required pressure \( H \), equivalent to \( p_{hr} \) at the heat carrier density \( \rho = 800 \) kg/m\(^3\), that is \( H = (12.5...125) \) Joule/kg the speed factor of the aggregates \( n_s \) lies in the range \( n_s = 40...60 \) [15].

2.1 Empirical dependency \( M_m = f(\dot{m}) \)

The reduced mass of a centrifugal pump \( M_m \) depends on:

- Efficiency factor,
- Pressure coefficient,
- Rotor speed \( n \) (rpm).
The first 2 parameters of a centrifugal pump characterize the efficiency of energy conversion in it. The number of revolutions \( n \) affects the intensity of energy transfer. When designing CEPU TCS spacecraft, developers to ensure the highest values of the specified parameters.

In the work [16], on the basis of empirical data, the graph \( M_m = f(\dot{m}) \), presented in Fig. 2. Approximation of this graphical dependence in the form of equation 3 is described by formula (3):

\[
M_m = 69.9 - 1.2 \cdot 10^3 \cdot \dot{m} + 7.6 \cdot 10^3 \cdot \dot{m}^2 - 1.6 \cdot 10^4 \cdot \dot{m}^3
\]  

(3)

Dependence (3) characterizes the achieved level of the reduced mass of the CEPU in the range of energy parameters \( \dot{m}, H \) and \( \omega \), corresponding to the parameters of single-phase TCS of telecommunication satellites. Formula (3) indicates a trend towards a decrease in the reduced mass of the CEPU with an increase in coolant flow rate \( \dot{m} \). At the same time, at the stage of preliminary design, equation (3) does not allow us to evaluate the nature of the change in the mass of the CEPU and the coefficient of speed \( n_s \) in the framework of the development of a unified series of CEPU for a given step of changing the pressure \( H \) or the angular speed of rotation of the rotor \( \omega \).

3 Results

The universal parameter that characterizes the influence of the energy parameters \( H, \dot{V} \) and \( \omega \) on the geometry of the CEPU impeller is the coefficient of speed \( n_s \):

\[
n_s = 193.3 \cdot \omega \sqrt{\dot{V}/H^{3/4}}.
\]  

(4)

On Fig. 3, in the axes the coordinate OH, \( \dot{V} \), for the conditions: \( n = 6000 \) rpm, \( \rho = 800 \) kg/m\(^3\), the level lines \( n_s = \) const and \( M_m = \) const, in order to illustrate the possible analysis of various schemes, changing the power of the unit using the parameters \( H \), and \( n_s \) when transition from point A \( (H_{initial}, \dot{V}_{initial}) \) according to the following 3 options:

- The AB line characterizes the variant \( H = \) var, \( \dot{V} = \) const, \( n_s = \) var,
• The AC line characterizes the variant \( H = \text{var}, \dot{V} = \text{var}, n_s = \text{const} \),

• The AB line characterizes the variant \( \dot{V} = \text{var}, H = \text{const}, n_s = \text{var} \).

For all 3 schemes of changing the pressure \( H \), the volumetric flow rate of the working fluid and the speed coefficient \( n_s \), the boundaries of the trajectories AB, AC, AD are on the lines of the level with a lower value \( \dot{M}_{\dot{m}} \). In particular, on the graph, points B, C and D are located on the same level line \( \dot{M}_{\dot{m}} = 15 \) sec, whereas point A is located on the line \( \dot{M}_{\dot{m}} = 20 \) sec. This means that the use of design solutions traditionally used in the design of the CEPU TCS spacecraft, the development of a high-power unit should be accompanied by an improvement in the specific mass characteristics of the construction.

**4 Discussion**

A separate comment requires an analysis of the result of the application of option 1. An increase in the pressure \( H \) due to a decrease in the speed coefficient \( n_s = \text{const} \) and \( n = \text{const} \) is accompanied by an increase in the radial dimensions and absolute mass of the centrifugal electric pump design. Obviously, within the given parameter \( \dot{M}_{\dot{m}} \), this should be accompanied by an increase in the value of \( M_\dot{m} \), which contradicts scheme 1. On the other hand, if the growth of \( H \) is due to an increase in \( n \), with a narrowing of the meridional section of the impeller channels, or an increase in the pressure coefficient, then such a modification of the CEPU meets the conditions for the implementation of scheme 1. This contradiction is due to the fact that the graphical dependence in Fig. 1 is local, not taking into account the requirements for generalized dimensionless characteristics.

**5 Conclusions**
An increase in the pressure coefficient $H$, rather than the number of rotations of the rotor $n$, is more preferable, since it is not accompanied by a deterioration in the anti-cavitation qualities of the CEPU and a decrease in the service life of the bearing units of the unit. However, such an approach requires time-consuming studies of the hydrodynamics of the flow in the cavity of the vessel and the improvement of methods for designing its flow form.

In general, the analysis carried out is of an evaluative nature in the preliminary design and planning of CEPU TCS spacecraft measures aimed at improving the specific mass indicators of centrifugal electric pump units.

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