Development of a mathematical model for the numerical study of a thermal control system fluid circuit

F V Tanasienko, Yu N Shevshenko, M G Melkozerov, A A Kishkin, A V Delkov and E V Khodenkova
Reshetnev Siberian State University of Science and Technology 31 Krasnoyarskiy Rabochiy Ave., 660037, Krasnoyarsk, Russia

E-mail: spsp99@mail.ru

Abstract. This paper considers the development of a mathematical model for spacecraft thermal control fluid circuit systems. The need to take into account the complex mode of heat exchange in a fluid circuit model reflects relevance of the paper. Basic equations of heat exchange model in the circuit are given. A procedure for the numerical solution is described. Obtained calculation results are presented and analyzed. The developed model allows numerical studies to assess an impact on characteristics of the circuit of various design and operating parameters.

1. Introduction
One of the main conditions for reliable functioning of a spacecraft and its service systems as well as payload equipment is to ensure appropriate thermal conditions all of its elements. However, this task in outer space conditions has its own specifics: there are various external radiation heat flows during a most of operational period on a spacecraft (thermal radiation from the Sun and the Earth) which can vary over a wide range (the temperature at different points of the spacecraft surface at the same time can be in the range from \(-150\) to \(+150\) °C). Also, a spacecraft thermal regime has a significant impact on onboard equipment power (which depends on the spacecraft operating modes). In this regard, the heat load is unstable.

Thermal control systems are used to ensure a temperature ramping of a spacecraft. The main thermal control systems task is to maintain the temperature at spacecraft nodal points in specified ranges due to the thermal energy redistribution and the excess thermal energy discharge into space.

Spacecraft thermal control systems may have different designs and operating principles. In this paper, we consider a thermal control system with a fluid circuit (FC) and heat exchange fluid pump circulation. Such systems are used in unsealed spacecrafts with power supply up to 5 kW [1]. Recently, fluid circuits have been used in many different spacecraft thermal control systems (International Space Station, Defense Satellite Program, space shuttle orbiter, Mars Pathfinder, Mars Exploration Rover, Mars Science Laboratory etc.) [2].

A schematic diagram of such a system is presented in figure 1. FC consists of payload heat exchange, a radiator panel, a pump and a connection tube system. A principle of operation of the fluid circuit is to transfer heat from heat dissipation areas (payload module devices, service system module) to areas of thermal discharge into outer space (radiator panels) with the help of heat exchange fluid flow. The circulation of heat exchange fluid is carried out with a pump. Fluid circuit topology is
determined by the location and power of the heat sources. Also, it can include elements with serial and parallel connection [3]. FC can be used to transmit large amount of heat by long distances [4]. The key feature of the fluid circuit is its closure because heat exchange fluid flow is constantly circulating between a source and a heat sink.

![Diagram of thermal control system fluid circuit](image1)

**Figure 1.** The scheme of thermal control system fluid circuit.

The fluid circuit location relative to the basic elements of a spacecraft is complex [5]. Figure 2 shows the spacecraft thermal control system fluid circuit layout in a honeycomb. Fluid circuit pipes are installed in honeycombs with special equipment. The honeycomb itself provides for a radiation surface to radiate heat into space. Consequently, this process of heat exchange in the FC is complex (conjugate) which simultaneously involves mechanisms of heat conduction, convection, and radiation.

![Diagram of spacecraft thermal control system fluid circuit](image2)

**Figure 2.** The spacecraft thermal control system fluid circuit layout.

There is a need to set and solve problems associated with a creation of computational and mathematical models for the fluid circuit of control systems arises in the process of developing modern layout schemes for instrument compartments of spacecraft [6]. Current existing mathematical models developed for circulating thermal control systems do not take into account specifics of complex conjugate heat transfer and do not allow the use of optimization procedures.

The creation of a mathematical model of the fluid circuit which makes it possible to assess influence of regime, geometric and thermal parameters on characteristics of a thermal control system is a promising scientific task which is considered in this study.
2. Mathematical model

Russian and foreign scientist use nodal mathematical models in the spacecraft thermal calculations practice. In a nodal thermal mathematical model, a physical object is represented as a number of isothermal nodes. A combination of nodes, geometric, thermal data for each node, thermal connections between nodes and interface with external environment make a thermal mathematical model.

Currently, software packages such as ANSYS, Thermica, ESATAN-TMS, SINDA, Radsol, etc. are widely used for thermal control systems calculations. However, most of these programs are very expensive. Also, integration with third-party applications is not always possible. Such programs have limitations, for example, it is impossible to take into account hydraulic features of a tract and it takes a lot of time to perform calculations for given boundary and initial conditions.

Therefore, the task of developing and creating special efficient algorithms for thermal control system fluid circuit characteristics calculating has great scientific and practical importance. Such an approach, along with ensuring the openness of the code, will make it possible to identify and take into account significant thermophysical processes and parameters that affect the operation of the system. Such parameters, for example, include heat exchange coefficient from liquid to the wall, combined actions of thermal radiation processes and radiator-emitter thermal conductivity, etc.

A feature of the spacecraft thermal control system fluid circuit is its complex hydraulic schematic and a presence of numerous wiring. In this paper, a principle of decomposition, according to which the system is divided into related elements, each of them is considered separately used to develop an algorithm for calculating parameters of the FC. In this case, it is possible to consider complex systems with any topology.

In this study, the problem of FC simulating is considered as a case of conjugate convective-radioactive heat exchange [7]. The present computational geometry model of the solid and fluid region (Fig. 2) corresponds to the combination of heat and mass exchange phenomena. There is heat equation (which describes conduction heat exchange) in the solid domain:

$$\rho c \frac{\partial T_s}{\partial t} = \nabla \cdot (k \nabla T_s)$$

There are three equations in the fluid domain for convection heat exchange:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

$$\rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = \rho g + \nabla p$$

$$\rho \frac{dh}{dt} = \nabla \cdot (k \nabla T_f) + \rho \frac{dq}{dt}$$

The boundary condition for convection heat exchange is defined as:

$$q_c = \alpha(T_s - T_i)$$

The boundary condition for radiation heat exchange is defined as:

$$q_r = c_0\varepsilon \sigma \varepsilon \left( T_s^4 - T_{out}^4 \right)$$

In these equations $\rho$ – density, $c$ – heat capacity, $t$ – time, $k$ - thermal conductivity, $T_s$ – temperature of solid domain, $u$ – velocity, $h$ – enthalpy, $p$ – pressure, $g$ – acceleration of gravity, $q_c$ – convection heat flux, $q_r$ – radiation heat flux, $\alpha$ – heat exchange coefficient, $\varepsilon$ – degree of blackness, $\sigma$ – Stefan-Boltzman's constant, $T_f$ – temperature of fluid flow, $T_{out}$ – outer space temperature.

3. Numerical solution

Resulting system of equations (1)...(6) can be solved numerically by using a finite difference method or finite element method [7]. From these equations, it is possible to define: temperature field in fluid...
domain; temperature field in the solid domain; pressure field in the fluid domain; velocity field in fluid domain.

There are number of essential features connected with existence of the equation system, set implicitly rather required parameters, at the solution of the equation system for a closed circuit [8]. Equations linearization is often difficult due to non-linear nature of temperature variations along the circuit length. Therefore, the use of standard matrix solution methods is impractical because calculations take a lot of time.

In this paper, the solution mathematical structure is in a feedback system. The solution algorithm is based on methods used for branched hydraulic networks using Kirchhoff’s laws [8]. Possibility of a solution consists of formalizing feedback as a boundary condition for the circuit (figure 3). Feedback fluid circuit means equality of parameters of heat exchange fluid (mainly temperature $t$) at inlet and at outlet with a one-pass passage of the circuit.

![Feedback fluid circuit](image)

Iterative methods are used to solve the problem [9]. The solution is constructed as follows: for a circuit arbitrary starting point, the initial condition on heat exchange fluid temperature ($t_0$) is set. Further, the circuit passes in the direction of flow until the return to the starting point. At the starting point, the condition of closure is checked: the equality of the values of heat exchange fluid temperature at the beginning and at the end of the calculation procedure ($t_0 = t_N$). The observed discrepancy is corrected and the next iterative step is performed. The exit condition from the iterative cycle is formed as:

$$\frac{t_{N(j)} - t_{N(j-1)}}{t_{N(j)}} < \xi(t)$$  \hspace{1cm} (7)

$T$ is heat exchange fluid temperature at the starting point, $j$ – the iteration step; $\xi$ – the permissible error value. The solution convergence rate depends on the initial value selection. In this study, minimum possible value of heat exchange fluid temperature its freezing temperature is used as the initial temperature.

4. Result analysis

Presented mathematical model and calculation algorithm allow conducting numerical fluid circuit studies with various topologies. In this paper, a configuration of the presented circuit is considered in Fig. 4 as a test task. The scheme includes two sections of honeycomb panels (1 and 5) with payload devices and radiation surfaces placed on them, two radiators (2 and 3) for thermal discharge into outer space and one service system module (4). Service system module is also a heat load source for the circuit. The two surfaces (1 and 2) are affected by solar radiation because of spacecraft orientation in an orbit.

According to the settlement scheme the fluid circuit passes through the honeycomb panel (1), then it is divided into two parallel branches going in two radiators (2 and 3), after that the fluid circuit unites again and goes to the service system module instrument board (4), then it passes through the honeycomb panel (2), and then again comes back to the honeycomb panel (1), closing the circuit.

Such elements as the thermal load of devices placed on each 4 kW honeycomb panel, the load of the utility system module 500 W were used as conditions for components of the design scheme as part
of the test task. The honeycomb panel (1) and radiator (2) are affected by solar radiation with a resultant flux density of 140 W/m².

![Figure 4. The design scheme of presented spacecraft thermal control system fluid circuit.](image)

Key feature of the scheme is radiator-emitter sections placement in the circuit in parallel in order to increase efficiency of radioactive heat release into space (intensity depends on the radiator surface temperature to the fourth power).

Fluid circuit characteristics were obtained at various heat load levels of the payload module and various heat exchange fluid flow rates for the present scheme. The temperature values at the base points of the fluid circuit (t₁...t₆, see figure 4) for the case of various heat load levels of the payload module are presented in Table 1. The table also shows the average temperature tavg of heat exchange fluid. The average temperature value is obtained for a closed circuit as the arithmetic average of temperatures t₁, t₂, t₅, t₆, t₁. The temperature t₁ is used 2 times as the temperature of the starting point (this point is the beginning and end of the circuit). Temperatures t₃, t₄ are not considered, since give the average t₅.

| №  | Heat loadings level, W | Honeycomb (1) t₁ | Honeycomb (5) t₆ | t₂ | t₃ | t₄ | t₅ | t₆ | tavg |
|----|-----------------------|------------------|------------------|----|----|----|----|----|------|
| 1  | 2000                  | 9.92             | 5.70             | 5.53| 0.34| 2.57| 1.46|     | 6.51 |
| 2  | 3000                  | 28.88            | 25.29            | 25.49| 19.37| 21.46| 20.42| 25.79|
| 3  | 4000                  | 42.57            | 39.99            | 39.93| 33.10| 35.14| 34.10| 39.83|
| 4  | 2000                  | 27.81            | 21.45            | 24.36| 18.29| 20.40| 19.35| 24.16|
| 5  | 4000                  | 26.93            | 26.19            | 23.43| 17.41| 19.51| 18.46| 24.39|

According to the data in table 1 it is seen that with an increase in heat load the average temperature of heat exchange fluid increases, which is due to its heat capacity (equation 1). The temperature varies smoothly relative to the base points of the circuit, there are no sharp jumps relative to the average temperature. This distribution is largely due to the convective nature of heat exchange in the circuit. With a symmetric change of load on honeycombs, the temperature run-up also increases slightly; all jumps of thermal loads are compensated for by the release of energy by radiation.

Thus, when using the model, average heat exchange fluid temperature in the circuit which determines the temperature level of cooled structures and devices it becomes possible to estimate. Such an assessment is especially important for sensitive instruments with strict requirements for temperature ranges.
Temperature values at the base points of the fluid circuit \((t_1...t_6)\) for the case of various heat exchanges fluid flow rates are presented in table 2.

**Table 2.** Temperature in base points at different heat exchange fluid flow rates.

| №  | Heat exchange fluid flow rate, kg/s | Base point temperature, °C |              |              |              |              |              |              |
|----|-----------------------------------|---------------------------|--------------|--------------|--------------|--------------|--------------|--------------|
|    |                                    |                           | \(t_1\)      | \(t_2\)      | \(t_3\)      | \(t_4\)      | \(t_5\)      | \(t_6\)      | \(t_{avg}\)  |
| 1  | 0.02                               |                           | 41.68        | 21.92        | 23.02        | -2.94        | 6.41         | 1.73         | 26.01        |
| 2  | 0.03                               |                           | 35.73        | 23.36        | 23.99        | 5.92         | 12.28        | 9.09         | 25.58        |
| 3  | 0.07                               |                           | 29.89        | 24.96        | 25.23        | 17.07        | 19.87        | 18.47        | 25.69        |
| 4  | 0.09                               |                           | 28.88        | 25.29        | 25.49        | 19.37        | 21.46        | 20.42        | 25.79        |
| 5  | 0.16                               |                           | 27.61        | 25.83        | 25.64        | 21.99        | 23.24        | 22.62        | 25.86        |

According to table 2, we can conclude that the flow rate is the determining parameter for thermal conductivity value of the circuit. With comparable levels of average temperature at different flow rates, different temperature amplitudes are observed as the circuit passes. With excessive expenses, temperature fluctuations along the length of the FC are not perceptible; the system comes to a state of thermal equilibrium for a given thermal load. On the contrary, insufficient consumption causes sharp fluctuations in temperature along the length of the FC. It becomes possible to optimize the circuit with the determination of the optimal flow rate of heat exchange fluid.

Results are consistent with expected according to the analysis of the system heat balance and correctly reflect the physical picture of heat exchange. In this way, the model can be used for the analysis of fluid circuits of a higher complexity level with the presence of various elements in series and parallel connected.

According to the analysis of computational experiment results for the spacecraft thermal control system fluid circuit, we can draw the following conclusions.

1. Changes in average heat exchange fluid circuit temperature due to changes in the heat load removed, which is associated with fluid heating under the action of heat, as well as the need for heat dissipation by radiation of large thermal powers, and hence by increasing the radiator-emitter temperature.

2. The flow rate of heat exchange fluid determines the temperature magnitude difference along the length of the fluid circuit. The higher the flow rate, the lower the temperature difference along the length of the fluid circuit. At excessive expenses of temperature fluctuation on a circuit, length is almost not notable, the system comes to a condition of thermal balance for the set thermal loading. On the contrary, insufficient flow causes sharp temperature fluctuations along the length of the fluid circuit.

3. The payload module heat redistribution between two symmetrical honeycomb panels for this arrangement does not have a significant impact on the efficiency of the fluid circuit (calculated cases 4 and 5 of table 1), which is an advantage of the scheme.

5. **Conclusion**

The present mathematical model for the spacecraft thermal control system fluid circuit allows evaluating the influence of constructive and regime influencing parameters on the efficiency of the thermal control system. The model can be used in a spacecraft design in the early stages and for conducting search engine optimization of spacecraft layout schemes. This mathematical model application will significantly reduce the amount of spacecraft thermal control system ground-based tests during a design process.

The series of computational experiments reflects the flexibility of the model, the adequate response to changes in external factors, and possibility of comparing thermal control system parameters across FC sectors in order to identify significant parameter, which was carried out by using authors' mathematical model and the calculation algorithm.
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