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HEAT TRANSFER COEFFICIENT CALCULATION FOR DEVELOPED AMMONIA BOILING IN THE EVAPORATOR CHANNEL OF A THERMAL SINK

The subject of this article is the heat transfer of ammonia in the channels of thermal sink evaporators. The objective was to determine a sufficiently simple correlation acceptable for engineering practice, which could be used to calculate the heat transfer in cylindrical channels of a thermal sink, designed for two-phase systems of thermal control systems of uncrewed spacecraft. For this purpose, experiments were performed on two thermal sink having an evaporator channel of ~7 mm diameter made of aluminum alloy and stainless steel, with channel surface roughness Ra 3.33 µm and 0.12 µm. The experiments were carried out with a subcooled liquid or two-phase flow at the channel inlet. The results of the experiments were compared with Kupriyanova's formula obtained under markedly different conditions: with ammonia boiling in a large volume on the external surface of 5...6 mm diameter tubes at –40 °C...+20 °C. It is shown that Kupriyanova's formula can be used on the ground and in microgravity conditions to calculate heat transfer coefficients during the developed boiling of ammonia in the range of flow parameters: saturation temperature +35 °C...+75 °C; mass velocity 27...200 kg/(sec-m²); liquid subcooling to saturation temperature at thermal sink inlet 0 °C...30 °C; mass vapor quality at the inlet 0...0.7. Difference of calculated and experimental values of heat transfer coefficients did not exceed 30 %.

Key words: spacecraft; thermal control system; two-phase mechanically pumped loop; thermal sink; evaporator.

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РОЗРАХУНОК КОЕФІЦІЄНТА ТЕПЛОВІДДАЧІ ПРИ РОЗВИНЕНОМУ КИПІННІ АМІАКУ В КАНАЛІ ВИПАРНИКА ТЕРМОПЛАТИ

У статті розв'язували задачу підбору кореляції, яку можна було б використовувати для розрахунку тепловіддачі в циліндричних каналах термоплат, призначених для двофазних систем забезпечення теплового режиму безлюдних космічних апаратів. Для цього було проведено експерименти на двох термоплатах і було показано, що формулу Купріянової можна використовувати на землі та в невагомості для розрахунку коефіцієнтів тепловіддачі під час розвиненого кипіння аміаку в характерному діапазоні параметрів потоку.

Ключові слова: космічний апарат; система терморегулювання; двофазний контур теплопереносу; тепловідвід; випарник.

Introduction

Thermal control systems (TCS) based on mechanically pumped two-phase loops (MPTPL) are the main innovation for high-power spacecrafts in recent decades [1], [2]. However, the heat transfer processes that take place in the heat transfer loop when the aggregate state of the coolant changes are insufficiently studied.

The key element of MPTPL is the thermal sink – a contact heat exchanger, on surface of which the components to be cooled are fixed. Inside the thermal sink there is a channel where the heat transfer liquid flows through. The advantage of two-phase thermal control systems is the use of heat transfer with developed boiling of the coolant, which allows to obtain high heat transfer coefficients and thus minimize the size and weight of heat exchange equipment [3], [4].

Both two-phase flow and subcooled liquid can flow into the thermal sink, so in practice it is necessary to determine the intensity of heat transfer in the channel at developed boiling in a wide range of coolant parameters. Especially limited information on calculation of heat transfer coefficients in the flow of liquid below to saturation temperature [5].

Considering that many factors (liquid parameters and properties, material and state of heat transfer surface, channel geometry, coolant flow parameters, gravity, etc.) influence on heat transfer in developed boiling, it is difficult to obtain universal calculation relation. Preliminary analysis carried out by the authors in [5] showed that the known methods of calculating heat transfer do not satisfy the practice. In the present work, we solved the problem of selecting a sufficiently simple correlation acceptable for engineering practice, to be used to calculate the average heat transfer coefficient in cylindrical channels of thermal sinks in the range of parameters, typical for thermal control systems of uncrewed spacecrafts. Ammonia was considered as a coolant, due to its high efficiency in this class of systems many authors have pointed out [6], [7].

Based on a literature review and our own studies, we identified the range of basic flow parameters typical of uncrewed satellites' thermal control systems:

- coolant saturation temperature +35 °C…+75 °C;
- mass velocity $G \approx 5...200$ kg/(sec-m²);
- average heat flux density on the evaporator wall q – up to 20 W/cm².

Methodology

Labuntsov [8] showed that there is a large area of flow parameters, when the local heat transfer in the channel at developed boiling can be calculated by correlations obtained for boiling at free convection (in a large volume). Labuntsov limited this area by the volume local vapor quality of the flow not more than 0.7. Preliminary analysis showed that our chosen range of study mainly corresponds to this area. But it was necessary to select a specific relation and verify it experimentally in the whole concerned for practice region of parameters [9].

As a result of literature review we chose for experimental approbation the correlation of A. V. Kupriyanova [10]. The author performed a series of experiments on ammonia boiling in a large volume on the outer surface of horizontal tubes in range of parameters: saturation temperature T_{sat} = –40 °C...+20 °C (P = 0.72...8.6 bar) and q = 2.3...8.7 W/cm². Based on these experiments, Kupriyanova determined the coefficients in the formula of G.N. Kruzhilin [11]. A simple, convenient for practical use dimensional correlation for the local heat transfer coefficient was recommended:

$$h = 2.2P^{0.21}q^{0.7}\,. \qquad (1)$$

The formula uses the following dimensions: h – W/(m²-K); q – W/m²; P – bar.

The formula does not contain any information on the material and roughness of the wall. Kupriyanova's experiments were carried out on "technically smooth steel pipes" with external diameter of 5...6 mm. The formula (1) obtained is recommended by the authors for calculation of the "boiling curve" with a decrease in the heat flux q in the region of developed boiling, when all the vaporization centers on the heat-exchange surface are activated. Possible hysteresis by heat load was not considered by the author.

Experiments

To confirm the applicability of Kupriyanova's formula for calculating parameters in TCS thermal sinks, a series of experiments were performed, which allowed verifying the formula (1) in a wider range than previously recommended by the author.

The experimental model of the thermal sink with side heating is shown in Fig. 1. The payload equipment is represented by dummy *1*, which is made of highly conductive material (Cu, Al), allowing it to be considered isothermal. Thermal power Q, W was supplied evenly from the top.

A detailed description of the experimental two-phase loop, thermal sink *1*, and the experimental procedure are presented in [9].

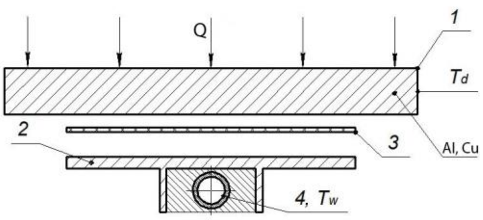


Fig. 1 – Cross section profile of the experimental thermal sink *2*: *1* – payload equipment dummy with heater on top; *2* – thermal sink; *3* – graphite layer; *4* – evaporator channel

The experiments were performed on two thermal sinks with significantly different design parameters of the evaporator channel:

Table 1 – Characteristics of thermal sinks

Parameter	Thermal sink	
	1	2
Diameter, mm	6.9	7
Length, mm	150	98
Channel material	Aluminum alloy	Stainless steel
Roughness Ra, µm	3.33	0.12
Heat transfer area, Fd, cm²	35.5	21.6

The experimental technique involved determining the average coefficient of heat transfer for the entire surface of the thermal sink evaporator channel using the formula:

$$h_{\exp} = \frac{q}{T_w - T_{sat}}\,, \qquad (2)$$

where q – average specific heat flux through the evaporator channel wall, W/m²;

T_{sat} – saturation temperature by pressure in the channel, °C;

T_w – average temperature of the evaporator channel heat heat-release surface, °C.

In the experiment, the temperature T_d of the surface *1* on which the heater was installed was measured. The average temperature of the heat dissipating wall of the evaporator channel T_w in the steady-state mode was calculated by the formula:

$$T_w = T_d - QR_{HRL}$$

or

$$T_w = T_d - qF_d R_{HRL}\,, \qquad (3)$$

where Q – input heat to the thermal sink, W;

F_d – heat dissipating wall area of the evaporator channel, m²;

R_{HPL}, K/W – thermal resistance of the thermal sink, calculated using SolidWorks and verified by test experiments.

More than 160 series of experiments were performed with different conditions of single-valuedness: saturation temperature T_{sat}, subcooling to saturation temperature ΔT_{sub} or mass vapor quality x_{in} at the channel inlet, mass flow rate m and orientation of the channel relative to the vector of gravity. Liquid underheated to saturation temperature or two-phase flow with mass vapor quality x_{in} was supplied to the inlet of thermal sink.

The experiments were performed in the following parameter range:

- saturation temperature by pressure T_{sat} = 35 °C…75°C;
- inlet fluid subcooling $\Delta T_{sub} = T_{sat} - T_{in}$ = 0 K…30 K;
- mass vapor quality at the inlet $x_{in} \approx 0…0.7$;
- mass vapor quality at the outlet

$x_{ex} \approx 0…0.95$;
- mass flow rate $m \approx 0.2...7.5$ g/sec;
- mass velocity: $G \approx 5...200$ kg/(sec-m²);
- average heat flux density $q \approx 0...18$ W/cm² (thermal sink *1*) and 0...9 W/cm² (thermal sink *2*);
- evaporator channel orientation – horizontal (heater at the top or at the bottom) and vertical.

The experiment measured:
- pressure in the evaporator thermal sink channel P_{HCA};
- mass flow rate of liquid m, g/sec;
- heater power Q, W;
- temperatures of coolant at the evaporator inlet and outlet T_{in} and T_{ex}, °C;
- surface temperature of the profile (9 sensors).

Instrumental errors of basic measurements are as follows: absolute pressure ±0.2 %; fluid mass flow rate ±0.2 %; temperature ±0.15 °C (0 °C), ±0.35 °C (100 °C).

The thermal sinks were carefully insulated. The heat loss was no more than 3 % of Q and was not considered in the analysis of the results.

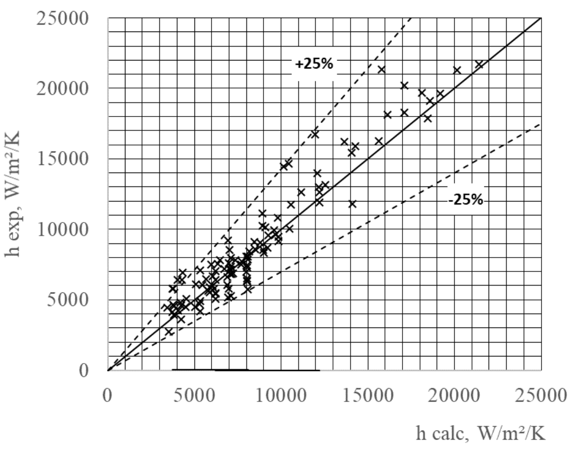
The value of the heat input to the thermal sink Q in each series of experiments varied from zero to the maximum value. Experimental points were fixed at steady-state conditions at different values of Q. As a result, a "boiling curve" was obtained – the dependence of the wall temperature T_w on the heat flux q, on which a zone of developed boiling was distinguished (details in [9]).

Results

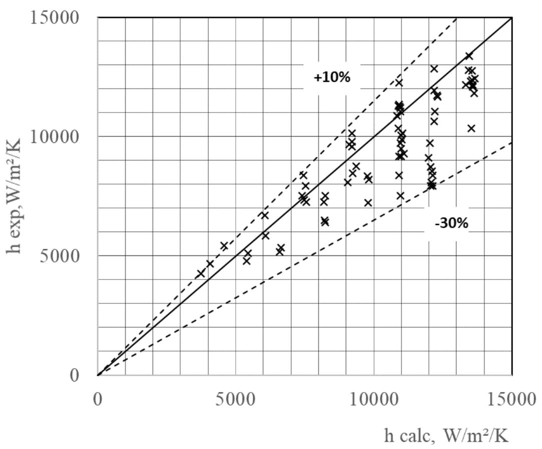
In the zone of developed boiling, the experimental heat transfer coefficient was calculated by formula (2). For the same points, heat transfer coefficient h_{calc} was calculated by formula (1), and the values of pressure P and average heat flux density q from the experiment were substituted into the formula. The results of comparing the calculation and experiment are shown in Fig. 2.

As was identified, Kupriyanova's formula (1) describes well the heat transfer of ammonia at developed boiling in the channel of both thermal sinks with an error of no more than 30 % in the following parameter range:
- saturation temperature
  T_{sat} = + 35 °C... + 75 °C;
- mass velocity G = 27…200 kg/(sec-m²);
- inlet fluid subcooling ΔT_{sub} = 0 °C...30 °C;
- mass vapor quality at the inlet x_{in} = 0–0.7.

The minimum flow rate $m_{\min} \approx 1$ g/sec was limited by the value of mass velocity $G \approx 27$ kg/(sec-m²). At lower flow rates, the heat transfer coefficient was affected by the orientation of the channel in the gravity field, which makes it impossible to recommend correlation for microgravity conditions. Although up to mass flow rate $m_{\min} \approx 0.4$ g/s (mass velocity $G \approx 10$ kg/(sec-m²)) the difference of experimental values of the heat transfer coefficient at the horizontal and vertical location of the channel did not exceed 5 %.



a



b

Fig. 2 – Comparison of experimental and calculated values of heat transfer coefficients: *a* – thermal sink *1*; *b* – thermal sink *2*

Following the recommendations of Labuntsov's work [9], the upper bound on the heat flux Q at developed boiling should be limited to the mass vapor quality at the thermal sink outlet x_{ex} ~ 0.7–0.8. However, as our experimental results have shown, satisfactory coincidence of calculation and experiment was observed up to the mass vapor quality at the outlet $x_{ex} \approx$ 0.85, which corresponds to the volume vapor quality at the thermal sink channel outlet φ_{ex} ~ 0.95. At the same time, the volume vapor quality was calculated taking into account phase slip [13].

Conclusions

Based on our own experiments on two thermal sink models, the possibility of using the Kupriyanova formula [11] to calculate the average heat transfer coefficient for developed boiling of ammonia in the evaporator channel of a thermal sink in the range of parameters characteristic of two-phase heat transfer loops of thermal control systems of unmanned spacecraft has been shown. Kupriyanova's correlation (1) is recommended for calculating boiling both in a subcooled liquid and in a two-phase flow, in weightlessness and on the ground, under the following conditions:

- saturation temperature by pressure T_{sat} = 35 °C...75 °C;
- mass velocity: $G \approx 27...200$ kg/(sec-m²);
- inlet fluid subcooling $\Delta T_{sub} = T_{sat} - T_{in}$ = 0 K…30 K;
- mass vapor quality at the inlet $x_{in} \approx 0…0{,}7$;
- mass vapor quality at the outlet $x_{ex} \approx 0…0{,}85$;
- volume vapor quality $\varphi_{ex} \approx 0…0{,}95$.

The difference between the calculated and experimental values of the heat transfer coefficient does not exceed 30 %.

The experiments were performed on two thermal sinks with significantly different material and roughness of the evaporator channel: aluminum alloy with roughness Ra 3.33 µm and stainless steel with roughness Ra 0.12 µm. Material and roughness in principle affect the nucleation of vaporization centers and, ultimately, the presence of heat flux hysteresis [14]. However, it is known that during developed boiling, when all vapor formation centers are activated, roughness and wall material (if it is well wetted by liquid) have almost no effect on heat transfer coefficient [12]. The conducted experiments confirmed this statement. Therefore, the formula is recommended for calculating the average heat transfer coefficient during developed ammonia boiling in evaporator channels made of any well-wetted material with different roughness outside the hysteresis zone.

Most of the experiments were performed on horizontally mounted thermal sinks with the heater placed on top of the evaporator channel (Fig. 1). Some of the experiments were performed with the heater placed at the bottom or with the coolant flowing vertically. Up to the mass velocity $G \approx 27$ kg/(sec-m²), no differences in the heat transfer rate were detected. At decrease of mass velocity up to $G \approx 10$ kg/(sec-m²) the difference of experimental values of heat transfer coefficient at horizontal and vertical channel arrangement did not exceed 5 %. Moreover, the horizontal orientation of the thermal sink with the heater on top gives a more conservative result. Therefore, Kupriyanova's formula can also be recommended for calculating heat transfer in weightlessness.

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