It is advisable to design thermal management systems for high-power stationary satellites and specific ground applications using two-phase mechanically pumped loops with ammonia as the coolant. During prolonged operation in orbit, the accumulation of non-condensable gases can occur due to radiolysis and chemical reactions. The issues related to the effect of non-condensing gas on system parameters and performance have not yet received sufficient attention.

The study of the distribution of non-condensable gas in the loop was performed by calculation-theoretical and experimental methods in a heat transfer loop with a Heat-Controlled Accumulator. Part of the gas accumulates in the steamgas zone of the Heat-Controlled Accumulator and affects the pressure value at a set temperature. The other gas is dissolved in liquid ammonia. This impacts the overheating of the cooled device when the heat load is switched on, the heat transfer intensity during boiling, and the cavitation reserve at the pump inlet. Accumulation of non-condensable gas up to ~0.075 mol nitrogen/kg ammonia, concentration of dissolved gas in the liquid up to ~$5.3 \cdot 10^{-4}$ mol/mol of the mixture does not significantly impact the parameters and performance of the system. But, if the aim is to precisely ensure the boiling temperature of the coolant or the cavitation reserve, the amount of necessary correction of the control parameters is up to 2.5 K.

The results of the investigation can be used in the design of two-phase heat transfer loops for satellites and other applications, in particular, for the selection of the design and location of gas traps

***Keywords:** two-phase heat transfer loop, non-condensable gases, heat-controlled accumulator*

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DETERMINING THE EFFECT OF NON-CONDENSABLE GAS ON A TWO-PHASE AMMONIA HEAT TRANSFER LOOP OF THE SATELLITE

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1. Introduction

It is rational to design thermal control systems (TCS) for powerful spacecraft on the basis of two-phase mechanically pumped loops (2PMPL) with ammonia coolant [1, 2]. They are more efficient in terms of weight, heat transfer intensity, thermal stabilization accuracy, coolant flow rate and power consumption for their natural needs compared to TCS based on single-phase liquid heat transfer loops. Despite their long history of development [2, 3], the first SES-17 and Eutelsat Konnect VHTS satellites manufactured by Thales Alenia Space-France with two-phase ammonia TCS were launched only in 2021 and 2022 [4, 5].

Scientific research into this area represents an important aspect in modern space engineering. Despite progress in this field, the influence of non-condensable gases (NCGs) in the coolant and in the loop itself remains insufficiently studied. The results of such studies are necessary in practice and could improve the reliability of both satellites with 2PMPL and various aviation and ground systems.

2. Literature review and problem statement

Work [6] provides a review of the possible consequences of NCG accumulation. An estimate was made of the amount of NCG in the 2PMPL of a geostationary satellite over 30 years of operation in orbit. The cause of the appearance of NCG is the radiolysis of ammonia and chemical reactions. NCGs can be in gaseous form and/or in solution and affect the performance of the system. The authors estimate the maximum amount of NCG in the loop to be 0.03 mol of hydrogen and 0.01 mol of nitrogen per 1 kg of ammonia. The fundamental possibility of the appearance of free NCG at the outlet of the 2PMPL condenser was shown. The value of the diffusion coefficient, which determines the rate of gas dissolution in the supercooled liquid after the condenser, was experimentally assessed. The rate of dissolution depends on the difference in gas concentrations in the bubble and in the liquid, however, the results reported in [6] are not related to the concentration of dissolved NCG in the liquid, which reduces the possibility of their practical use. The presence of NCG in free form can lead to an increase in the hydraulic resistance of chokes and filters; it can block the operation of pumps, heat exchangers and evaporators with capillary-porous structures [7]. Free NCG in the fluid stream upstream of the pump (in the form of bubbles) can lead to problems with cavitation and pump starting [6]. However, the cited works do not provide a critical value of NCG, which can negatively affect the performance of 2PMPL.

Works [2, 3] show that already in the first 2PMPL projects for large space platforms in the 1980s, the developers took into account the requirement that the system be insensitive to blocking of paths by non-condensable gases. To localize and remove free NCG, gas traps of different operating principles installed in different places of the loop were considered. Gas traps were included in the projects of Grumman, RSC Energia, and the European Columbus station. Gas traps are also used in single-phase heat transfer loops in the American segment of the International Space Station (ISS) [8]. In the Sundstrand and Boeing project, the separation and removal of NCG was provided for in the multifunctional unit – Rotating Fluid Management Device (RFMD). However, works [2, 3, 8] lack justification for the need for gas traps, their design and volume, and installation location in the loop.

In [9], experiments were carried out to determine the effect of NCG on the heat transfer coefficient. The experiments were performed with a stainless-steel heater with a diameter of 25.4 mm. Range of operating parameters: pressure 1–7.9 bar, flow rate 106–761 kg/m^2/s, heat flow 800–375000 W/m^2, natural and forced convection in the flow of subcooled dielectric coolant R-113. The authors showed that the heat transfer coefficient for liquids containing dissolved NCG is always greater than for degassed liquids. The authors of [10], using the FC-72 heat carrier, showed that the heat transfer coefficient in the region of low heat flow exceeded the heat transfer coefficient in the degassed heat carrier. But in the region of high heat flow, the heat transfer coefficients did not differ significantly.

Work [11] reports the results of studies of heat transfer at low concentrations of NCG. It has been shown that at a concentration of NCG of 0.0025 mol of gas/mol of liquid, the dissolved gas does not affect the heat transfer coefficient at developed boiling. However, when the amount of dissolved gas in a liquid increases to a value of 0.0056 mol gas/mol liquid, the heat transfer coefficient increases. In [12], they conducted a study of the influence of dissolved gas on the boiling of subcooled liquid under weightlessness conditions on board the Japanese space experimental module «KIBO». The coolant used was PFH, a tube with an internal diameter of 4 mm. At low heat flows, an increase in the heat transfer coefficient was observed, while at high heat flows there was no effect. The reason for the increase in the heat transfer coefficient in the presence of NCG may be that in a larger number of active vaporization cavities on the surface, steam will be desorbed, which will improve the conditions for the formation of «viable» bubbles. The influence of the partial pressure of the dissolved gas also reduces the critical radius of the bubble. Works [11, 12] recorded the presence of local overheating at the moment of the onset of boiling. An explanation of this phenomenon is given in [13]. This overheating is associated with hysteresis in thermal load. However, no in-depth study of this phenomenon has been carried out.

Studies [9–13] do not provide systematic information about the influence of NCG on the processes of ammonia boiling on various surfaces, at different heat flows, which predetermines the need for further research.

In [14], the influence of NCG on the cavitation reserve (NPSH)was studied. It is well known that dissolved NCG in a liquid coolant to an earlier onset of cavitation in the pump. However, existing models for calculating cavitation reserve are applicable in a narrow range of initial data. In addition, there is no experimental information on cavitation when using ammonia as a heat carrier. Therefore, it is advisable to conduct additional authentic research.

From the above literature [2–14] it is clear that NCG can have a significant impact on the parameters in 2PMPL. The information available is limited and sometimes contradictory. Analysis of the distribution of NCG in the loop was not carried out. The studies were carried out at low concentrations of dissolved NCG. In addition, heat transfer conditions and overheating have been studied exclusively at the local level while engineering practice is interested in the intensity of heat transfer in cold plate at the integral level, at the device level.

This predetermines the need to analyze the distribution of NCG in 2PMPL, its influence on the parameters of the loop, on the phenomenon of hysteresis in thermal load, on the heat transfer coefficient during boiling, on the onset of cavitation of the pump. Practitioners are also interested in recommendations on the design and location of gas traps.

3. The aim and objectives of the study

The purpose of the study is to determine the effect of NCG, on a two-phase ammonia heat transfer loop in the satellite. This allows us to formulate recommendations for the design of 2PMPL to promising geostationary communication satellites with a long operating time in orbit.

To achieve the goal, the following tasks were set:

– to determine the distribution of NCG in dissolved and free form in the loop, the magnitude of the mismatch between the measured pressure and the saturation pressure in HCA. Formulate recommendations on the design and installation location of gas traps;

– to obtain experimental data on overheating of a cooled device due to the phenomenon of hysteresis in terms of thermal load;

– to study the influence of NCG on the intensity of heat transfer during developed boiling in cold plate of various designs;

– to determine the required cavitation reserve at various concentrations of NCG.

4. Materials and research methods

4. 1. Experimental model of the heat transfer loop

This study aims to investigate the influence of dissolved and free NCG concentrations on 2PMPL parameters related to thermal performance. The object of the study is a two-phase heat transfer loop with pumping using ammonia heat carrier.

It should be expected that part of NCG will accumulate in the steam zone of the hydraulic accumulator, and part will dissolve in liquid ammonia. In this case, the presence of NCG in the steam zone will lead to an increase in pressure compared to the saturation pressure in temperature, and the presence of dissolved NCG will lead to a decrease in overheating of cooled devices when the heat load is turned on, to a change in the heat transfer coefficient and cavitation reserve. To test this statement and obtain quantitative information, an experimental bench, which was a simplified analog of a standard 2PMPL, and a thermodynamic model of the coolant in the loop were used.

For experimental studies, a pumping heat transfer loop in the form of a single loop was used, a simplified diagram of which is shown in Fig. 1.

A diagram of the experimental cold plate is shown in Fig. 2.

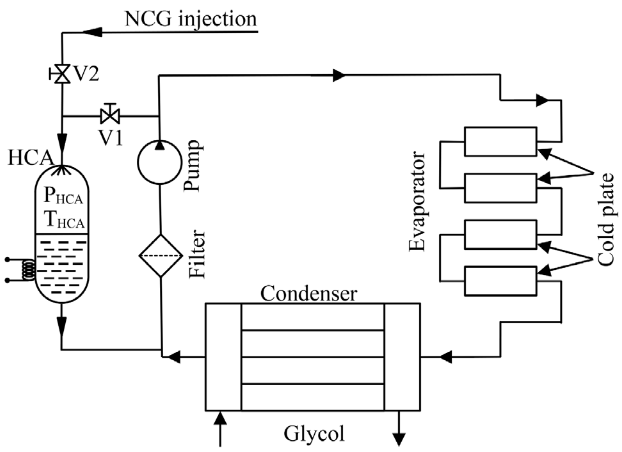

Fig. 1. Diagram of the experimental bench

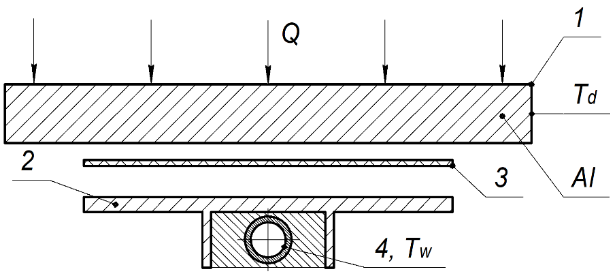

Fig. 2. Diagram of the experimental cold plate: 1 — heater (device) simulator; 2 — cold plate housing; 3 — graphlex plate; 4 — evaporator channel; T_w — evaporator wall temperature; T_d — temperature of the device simulator

The pump circulates coolant (ammonia) along the loop through the evaporator and condenser. The evaporator is a steel tube with a diameter of 7 mm, on which 10 cold plate (contact heat exchangers) of different designs are installed. Fig. 2 shows a diagram of the design of one of the cold plate with an installed device simulator. In the condenser, heat is removed using cold glycol.

The pressure in the loop is regulated using a heat-controlled accumulator (HCA). HCA also performs the functions of a separator of free NCG and a compensator for changes in the volume of liquid in the loop. It was possible to circulate part of the coolant through the HCA if valve V1 was opened. The loop is equipped with two inspection windows before and after the evaporator to observe the presence of vapor-gas phase bubbles in the liquid flow.

The total volume of the experimental loop is V^{Σ}=8.7 liters. It includes a HCA volume V^{HCA}=5.5 liters and a loop volume of 3.2 liters.

Under a two-phase operating mode, part of the loop, including the evaporator, condenser, and the transport line between them, is filled with a two-phase coolant with a high vapor content. Volume of two-phase elements (without economizer section and subcooling section) V^{2f}~1.28 liters.

The experiments were carried out with one filling of the system with degassed ammonia in the amount of $M_1^{\Sigma} = 3.104$ kg. Gas (nitrogen) was introduced into HCA through valve V2 in the amount of m_{2x}=0.025, 0.05. and 0.075 mol of nitrogen per 1 kg of filled ammonia. This significantly exceeded the predicted accumulation of NCG (in moles) in the loop during long-term operation in orbit [6].

The experiments were performed in the following sequence. The required amount of nitrogen was introduced into the HCA. The dissolution of the gas in ammonia to an equilibrium state was ensured, for which the loop operated for a long time under a single-phase mode with recirculation of part of the liquid through the HCA (through valve V1). Then, heat was supplied to the cold plate and experiments were performed under a two-phase mode. The necessary measurements of parameters were carried out under stationary modes.

The experiments were performed on ammonia at two coolant temperatures in the HCA T_{HCA}=35 °C and 55 °C, which approximately corresponds to the level of operating temperatures in standard systems.

4. 2. Thermodynamic model of the coolant in the presence of non-condensable gases in the loop

To analyze the concentration of NCG in the liquid and gas phases and the pressure in the HCA in an equilibrium state, a thermodynamic model of «ideal solutions» was built. The use of the «ideal solution» model is justified as follows.

In the gas phase there is a mixture of gases (nitrogen, ammonia at relatively low pressures), the equations of state of which can be calculated in the ideal gas approximation. In this case, Darcy's law is applicable, which is an independent property of ideal gas mixtures.

In the liquid phase there is a solution of NCG with an extremely low concentration, which can be considered ideal; the laws of Raoult, Henry, and Amag can be used.

In accordance with the real loop, an «equivalent volume» was set – a container in which there is an equilibrium mixture of ammonia and NCG (nitrogen) in a two-phase state (Fig. 3). The following are predefined: mass of ammonia M_1^{Σ}, «equivalent volume» V^{Σ}, temperature T_{HCA}, molal concentration of nitrogen $m_{2x} = n_2 / M_1^{\Sigma}$.

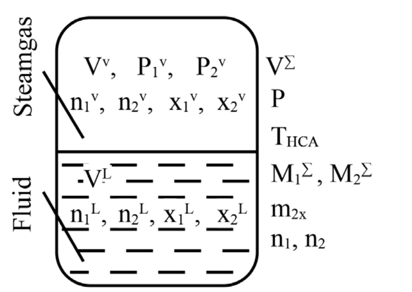

Fig. 3. Thermodynamic model of the coolant

In the «equivalent volume» two zones can be distinguished: vapor gas V_V (a mixture of gaseous nitrogen and ammonia vapor) and liquid V_L (a solution of nitrogen in liquid ammonia). Vapor gas and liquid are in thermodynamic equilibrium.

Under a single-phase mode, a liquid supercooled coolant circulates in the loop. Due to fluctuations and the flow of part of the coolant through valve V1 (Fig. 1), mass transfer occurs between the liquid in the loop and in HCA. Therefore, the concentration of dissolved gas in the liquid zone of HCA and in the loop during long-term stationary operation is the same. Obviously, this equality remains true under a two-phase mode.

The value of the «equivalent volume» V^{Σ} was taken equal to the volume of the HCA+the volume of liquid in the loop.

To calculate the parameters of the mixture state, the following assumptions were adopted:

– the solution of gas in liquid has a very low concentration, so it can be considered ideal;

– vapor gas is a mixture of ideal gases.

Estimates show that in the studied range of parameters such assumptions are quite acceptable.

The complete system for calculating the equilibrium state included the equations:

– material balance;

– constancy of the total volume of the system (HCA+loop);

– state of gas and liquid;

– conditions of phase equilibrium of the mixture.

It is known that the thermodynamic equilibrium of a mixture is determined by the equality of the chemical potentials of the phases of each component at a given temperature in a container T_{HCA} [15]. Within the accepted assumptions, the conditions for the phase equilibrium of ammonia and nitrogen are written in the form of two equations:

– Henry's law:

$$P_2^V = K(P,T)\cdot x_2^L; \quad (1)$$

– Raoult's Law:

$$P_1^V = P_{sat}(T)\cdot x_1^L, \quad (2)$$

where P_2^V, P_1^V is the partial pressure of nitrogen and ammonia in the steam gas; x_2^L, x_1^L – molar concentration of nitrogen and ammonia in the liquid; $P_{sat}(T)$ – ammonia saturation pressure at a given temperature T; $K(P, T)$ – Henry's coefficient at a given temperature $T=T_{HCA}$ and pressure $P=P_{HCA}$. The Henry coefficient was assigned as a result of analysis of our own experiments and data from works [13, 16].

5. Results of investigating the influence of non-condensable gases

5. 1. Distribution of non-condensable gases in the loop, the magnitude of the mismatch between the measured pressure and the saturation pressure in HCA

The concentration of NCG in dissolved and free form, and the pressure in HCA were calculated using a thermodynamic model. The model was validated by comparing the experimental and calculated pressure mismatch values.

Under a single-phase mode, the value of the «equivalent volume» of the system V^{Σ} was taken equal to the total volume of the system (loop+HCA): V^{Σ}=8.7 liters. Under a two-phase mode in the loop, as a result of boiling of the coolant in the cold plates, two-phase areas with a high vapor content appear and part of the liquid flows into the HCA, reducing the volume of the vapor-gas zone in the HCA. It is accepted that the volume of the steam cavity in the loop at a maximum thermal load of ~500 W is ~0.6 V^{2f}~0.77 liters. Therefore, the «equivalent volume» of the system V^{Σ} under a two-phase mode is conditionally reduced by this amount and amounted to V^{Σ}=7.93 liters.

The results of variant calculations are given in Table 1 and shown in Fig. 4.

In Table 1: M_2^{Σ} – total mass of nitrogen in the system; M_2^V – mass of dissolved nitrogen in the liquid; V^V is the volume of the vapor-gas zone in HCA; x_2^L, x_2^V – calculated molar concentration of nitrogen in liquid and vapor gas, mol nitrogen/mol mixture; ΔP_{cal}, ΔP_{exp} – calculated and experimental pressure mismatch in HCA:

$$\Delta P_{cal} = P_{cal} - P_{sat}(T_{HCA}), \quad (3)$$

$$\Delta P_{exp} = P_{exp} - P_{sat}(T_{HCA}), \quad (4)$$

where P_{cal}, P_{exp} is the pressure in the system, calculated or measured in the experiment. ΔP_{cal} is almost equal to the partial pressure of nitrogen in the steam gas P_2^V.

Table 1

Equilibrium state of the system (calculation, experiment) $M_1^{\Sigma}=3.104$ kg

N	1			2			3			4		
Mode	One-phase						Two-phase					
V^{Σ}, L	8.7						7.93					
T_{HCA}, °C	35			55			35			55		
m_{2x}	0.025	0.05	0.075	0.025	0.05	0.075	0.025	0.05	0.075	0.025	0.05	0.075
M_2^L/M_2^{Σ}	0.28			0.347			0.373			0.46		
V^V/V^{Σ}	0.398			0.365			0.289			0.251		
$x_2^V\cdot 10^4$	296	575	838	185	363	534	350	677	983	219	429	630
$x_2^L\cdot 10^4$	1.211	2.422	3.633	1.498	2.997	4.495	1.443	2.885	4.327	1.784	3.568	5.352
P_{sat}, bar	13.51			23.11			13.51			23.11		
$\Delta P_{cal}\approx P_2^V$, bar	0.41	0.82	1.23	0.431	0.862	1.293	0.488	0.977	1.465	0.513	1.027	1.54
ΔP_{exp}, bar	0.4	0.8	1.07	0.516	0.902	1.248	0.43	0.78	1.09	0.52	0.985	1.375

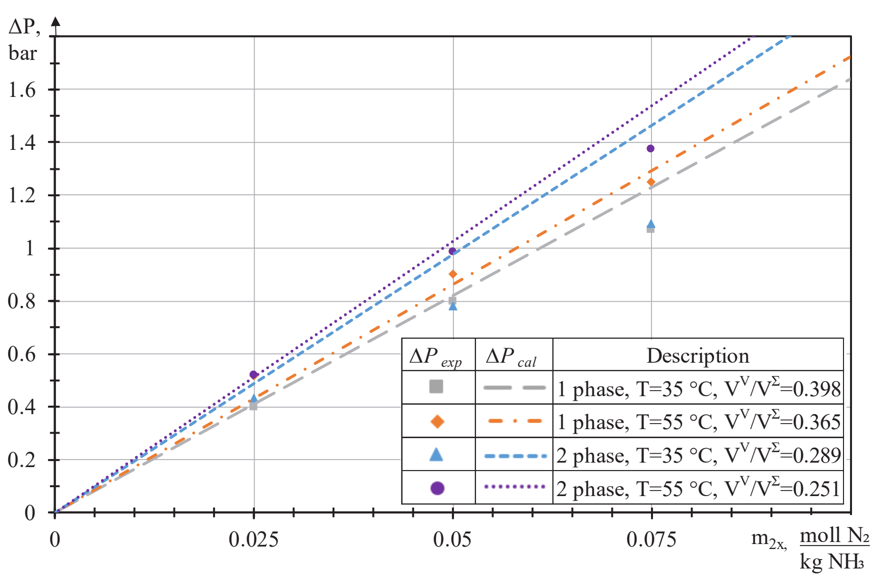

Fig. 4. Pressure mismatch in a heat-controlled accumulator after nitrogen injection

The experimental pressure mismatch in the hydraulic accumulator (ΔP_{exp}) is an objective, easily determined parameter, depending on the presence of NCG (m_{2x}) in the system. Table 1 gives and in Fig. 4 shows the experimental values of ΔP_{exp}, which correlate quite well with the calculated values of ΔP_{cal}, which indicates the adequacy of other calculated parameters.

5. 2. Influence of non-condensable gases on hysteresis under thermal load

With an increase in thermal load Q, when the loop transitions from a single-phase to a two-phase operating mode, for boiling to occur, it is necessary that the wall of the cold plate evaporator channel be overheated relative to the saturation temperature ($T_w > T_{sat}$). As a consequence, overheating is also observed at the level of the cooled device ($T_d > T_w > T_{sat}$).

Fig. 5 shows the classic «boiling curves» – plots of changes in the temperature of the device with the increase ($T_{d.inc}$) and decrease ($T_{d.dec}$) depending on the heat flux density in the evaporator channel (q).

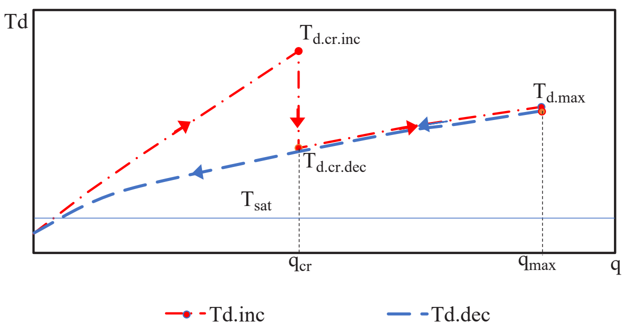

Fig. 5. «Boiling curves» – the phenomenon of hysteresis in terms of thermal load: q_{cr}, q_{max} – critical and maximum heat flux; $T_{d.max}$ – device temperature at maximum heat flow

With an increase in heat flux at $q = q_{cr}$, the temperature (T_d) of the device decreases sharply, which indicates a transition of heat transfer from single-phase convection to developed boiling. In the reverse process of reducing the thermal load from q_{max}, the temperature of the device (T_d) decreases monotonically, smoothly, without jumps. The different behavior of dependences $T_d = f(q)$ with increasing and decreasing q is called «thermal load hysteresis». The maximum overheating of the device $\Delta T_d = T_{d.cr.inc} - T_{d.cr.dec}$ can be significant; $\Delta T_d \approx 18$ K was observed in experiments [13]. This may affect the reliability of the device.

Studies of the influence of NCG on hysteresis in cold plate N1 were carried out using a method that included two experimental scenarios. The first scenario assumes a slow quasi-stationary change in the heat load and the construction of classical boiling curves such as those shown in Fig. 5. The second scenario involves rapid heating of the cold plate after turning on the thermal load immediately at full power q_{max}. The procedure is described in more detail in [13].

Fig. 6 shows the results of experiments under scenario 1 for cold plate H1 (Fig. 2). In the cold plate: evaporator wall material – stainless steel, wall roughness $Ra = 0.12$ µm. Conditions for unambiguous experiments include:

– $T_{sat} = 55$ °C (calculated from the pressure in the cold plate);

– $\Delta T_{sub} = T_{sat} - T_{in} = 10$ K, subcooling of the liquid at the inlet to the cold plate, where T_{in} is the temperature of the liquid at the inlet to the cold plate;

– $m = 4.5$ g/s, ammonia flow rate.

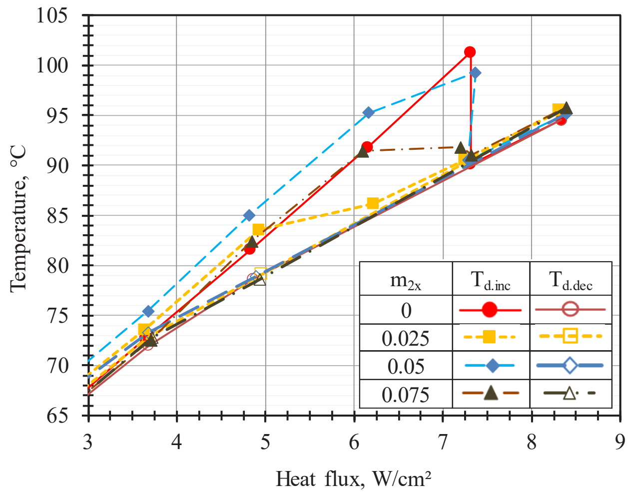

Fig. 6. Boiling curves at various concentrations of non-condensable gases according to experimental scenario 1

It can be seen that an increase in the concentration of NCG leads to a decrease in temperature $T_{d.cr.inc}$ and maximum overheating of the device ΔT_d.

Fig. 7 shows experiments under scenario 2 at different concentrations of NCG, under the same conditions of unambiguity, but for different maximum heat fluxes q_{max}.

The heating schedule of the device depends on the value of q_{max}. At $q_{max} = 5$ W/cm^2 there was no boiling under the stationary mode, no hysteresis was observed. At $q_{max} > 5$ W/cm^2, heat transfer under a stationary mode occurred in the presence of boiling. It can be seen that at low concentrations of NCG, the attainment of a stationary regime of developed boiling occurred with a temperature jump, $T_{d.max} - T_{d.st.max} > 0$. In the presence of NCG in the loop $m_{2x} \approx 0.05...0.075$ mol nitrogen/kg ammonia, the concentration of dissolved gas in the liquid is $x_2^L \times 10^4 \approx 3...5$ mol/mol of the mixture, boiling usually begins without noticeable overheating of the device, $T_{d.max} - T_{d.st.max} \approx 0$.

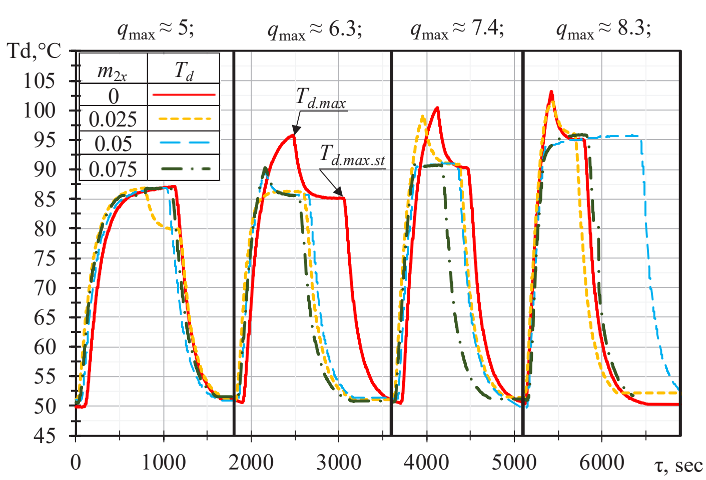

Fig. 7. Scenario 2 experiments on the H1 cold plate, $T_{sat} = 55$ °C, $\Delta T_{sub} = 5$ K, $m = 4.5$ g/s

Thus, the general conclusion is the following: NCG helps reduce overheating of the device when cold plate are turned on due to the phenomenon of hysteresis.

5. 3. The influence of non-condensable gases on the heat transfer coefficient at developed boiling in a cold plate

To determine the average experimental heat transfer coefficient in a cold plate, the following formula is used:

$$h_{exp} = \frac{q}{[T_d - q \cdot F_d \cdot R_{HPL} - T_{sat}(P)]}, \quad (5)$$

where q is the heat flux density in the evaporator channel W/cm^2, T_d is the temperature of the device, K, F_d is the heat transfer surface of the evaporator channel, cm^2; R_{HPL} – thermal resistance of the cold plate design, K/W; P – pressure in the cold plate evaporator.

It was shown in [16] that when developed boiling occurs over the entire surface of the evaporator channel, then the experimental results for pure ammonia correlate well with the calculated heat transfer coefficient calculated using the formula:

$$h_{cal} = 2.2 \cdot P^{0.21} q^{0.7}. \quad (6)$$

(6) employs the following dimensions: h_{cal} – W/(m^2·K), P – bar, q – W/m^2.

Tables 2, 3 give the experimental and calculated values of the heat transfer coefficients for 4 cold plate of different designs H1, NE3, NE1, HDH3. The diameter of the evaporator channel was the same, 7 mm. To guarantee heat transfer mode at developed boiling, the heat flux density must be maximum, ($q_{\max}$). The experiments were carried out at four values of the molar concentration of nitrogen (m_{2x}). Since heat transfer is affected by the amount of dissolved gas in liquid ammonia, the calculated value of the molar concentration of nitrogen in the liquid at the inlet to the thermal board x_2^L is indicated separately.

Table 2

Main characteristics of experimental cold plates

Cold Plate	H1	NE3.1	NE1.1	HDH3
Material	AISI 316	AISI 316	AISI 316	Al
Ra, μm	0.12	0.12	1.99	3.3
L, mm	98	370	370	150
$q_{\max}$, W/cm^2	8.3	6.2	6.3	11.5

It can be seen that in cold plate H1 and NE3 the presence of NCG did not affect the heat transfer coefficient. In the NE1 cold plate, with increasing NCG, the experimental heat transfer coefficient (h_{exp}) decreased by ~25 %, and in the HDH3 cold plate, on the contrary, it increased by ~25 %. The calculated heat transfer coefficient (h_{cal}) is practically unchanged. This ambiguous result correlates with literature data. Thus, a general conclusion can be drawn that the effect of dissolved NCG on the heat transfer coefficient is insignificant, especially at x_2^L concentrations up to approximately $5 \cdot 10^{-4}$ mol nitrogen/mol mixture.

5. 4. The influence of non-condensable gases on the onset of pump cavitation

It is known that when a liquid with dissolved gases is supplied to the pump inlet, steam cavitation is preceded by gas cavitation [14]. The presence of dissolved gas promotes an earlier onset of cavitation.

Cavitation reserve is usually determined in terms of pressure using the formula:

$$\Delta P_{cav} = P_{in.p} - P_{sat}\left(T_{in.p}\right), \quad (7)$$

where $P_{in.p}$, $T_{in.p}$ – pressure and temperature of the liquid at the pump inlet.

The available cavitation reserve in a degassed liquid can also be determined through temperatures:

$$\Delta T_{cav.a} = T_{sat}\left(P_{in.p}\right) - T_{in.p}. \quad (8)$$

In order to determine the effect of NCG on the onset of cavitation, experiments were carried out at various values of m_{2x} according to the following scenario. After performing the procedure for dissolving the NCG, the loop was switched to single-phase mode. With constant flow, temperature and pressure in the HCA, the pump inlet temperature ($T_{in.p}$) slowly increased until cavitation began. The onset of undeveloped cavitation was determined by a sharp increase in flow rate fluctuations (m), but at the same time the pump pressure (H) changed slightly. The onset of developed cavitation was determined by a sharp decrease in pump pressure (Fig. 8).

Based on the experimental data, the available cavitation reserve was calculated. If the cavitation reserve was determined from measured temperatures, then it was calculated using the formula:

$$\Delta T_{cav} = T_{HCA} - T_{in.p}. \quad (9)$$

Table 3

Heat transfer coefficient in cold plates, Tsat~55 °C, ΔTsub~5 K, m=4.5 g/s

Cold Plate		H1			NE3.1			NE1.1			HDH3		
m_{2x}	$x_2^L \cdot 10^4$	$T_{d.max}$	h_{exp}	h_{cal}	$T_{d.max}$	h_{exp}	h_{cal}	$T_{d.max}$	h_{exp}	h_{cal}	$T_{d.max}$	h_{exp}	h_{cal}
0	0	96.4	10332	13359	73.7	12239	10816	70.3	8763	11025	83.1	15756	16678
0.025	1.784	95.8	10656	13305	73.9	12223	10798	71.1	7953	10835	82.5	19999	16809
0.050	3.568	95.9	10649	13283	73.7	12556	10792	71.9	7120	10816	81.5	22851	16709
0.075	5.352	95.9	10388	13228	74.1	12209	10810	72.9	6466	10851	81.4	21290	16495

If the measured pressure in the HCA and the temperature at the pump inlet were used, then the cavitation reserve was calculated using formula (9), and it was accepted: $P_{in.p}=P_{HCA}$. It is obvious that in a degassed liquid formulas (8) and (9) are equivalent.

Fig. 8 and Table 4 show the parameters of several experiments.

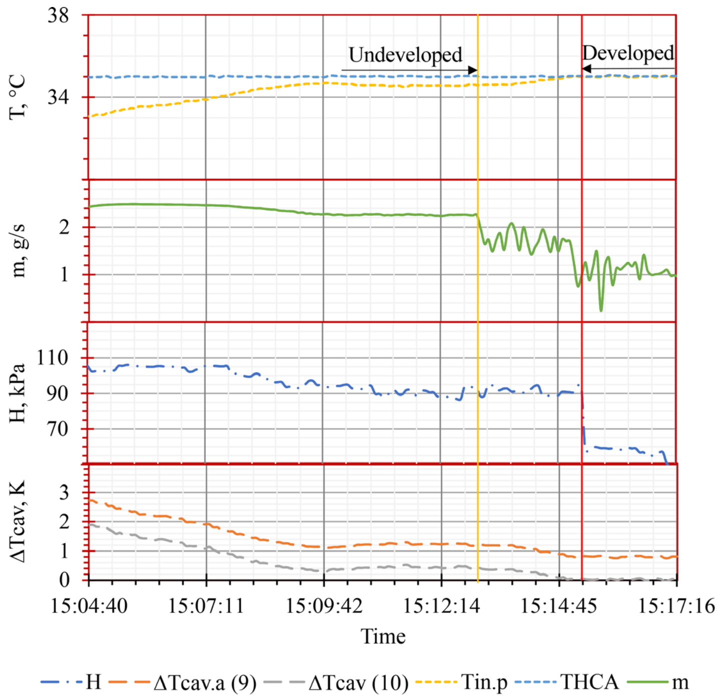

Fig. 8. Experiment to determine the onset of cavitation: T_{sat}=35 °C, m=2.5 g/s, m_{2x}=0.05

Table 4

Selected experimental data on the onset of cavitation

m_{2x}, mol nitrogen/kg ammonia		0	0.05	0.075
$x_2^L \times 10^4$, mol/mol mixture		0	2.4	4.5
T_{HCA}, °C		35	35	55
P_{HCA}, bar		13.5	14.3	24.36
$T_{sat}(P_{HCA})$, °C		35	37	57.1
Undeveloped	$\Delta T_{cav.a}$, K	~0.3	~1.2	~2.9
	ΔT_{cav}, K	~0.3	~0.4	~1.2
Developed	$\Delta T_{cav.a}$, K	–	~0.8	~1.7
	ΔT_{cav}, K	–	~0.0	~0.1

It can be seen that with an increase in the temperature of the liquid at the pump inlet ($T_{in.p}$), undeveloped and then developed cavitation is first observed. As the concentration of dissolved NCG increases, the values of $\Delta T_{cav.a}$ and ΔT_{cav} at which cavitation begins (required cavitation reserve, NPSHr) increase. In this case, $\Delta T_{cav.a}>\Delta T_{cav}$. In the experiments, the maximum concentration of dissolved NCG was low, $x_2^L \times 10^4 \approx 4.5$ mol nitrogen/mol ammonia. But at the same time, the required cavitation reserve compared to the degassed liquid increased by ~1.5–2.5 K. If the pressure in the loop is regulated by the value of the cavitation reserve, then when NCG accumulates, it is necessary to adjust the control program.

6. Discussion of results of investigating the influence of non-condensable gases on the performance and parameters of the system

According to estimates from [6], the amount of NCG that can be accumulated in the ammonia heat transfer loop of a stationary satellite during operation for up to 30 years in orbit is 0.04 mol/kg of ammonia. Our study examined the effect of NCG on the parameters of the loop at a maximum molal concentration of NCG up to $m_{2x}\approx$0.075 mol nitrogen/kg of ammonia, which is significantly higher than the forecast. In this case, the molar concentration of NCG in the liquid x_2^L in the studied range of parameters was no more than $5.3\cdot10^{-4}$ mol nitrogen/mol of mixture (Table 1).

Experiments and calculations show (Table 1) that the fraction of the mass of dissolved nitrogen M_2^L / M_2^Σ and the molar concentration of nitrogen in the liquid x_2^L increase with increasing temperature and with the transition to a two-phase operating mode. The molar concentration of nitrogen dissolved in the liquid x_2^L in the range of studies performed is very low. For example, under a two-phase mode at m_{2x}=0.05 and T_{HCA}=55 °C, it is only $3.6\cdot10^{-4}$ mol of nitrogen/mol of ammonia. This indicates the validity of the assumption that the solution of nitrogen in ammonia is ideal. The molar concentration of nitrogen in steam gas x_2^V is more than two orders of magnitude higher.

The main part of the NCG accumulates in the vapor-gas zone of HCA, which can act as a gas trap, localizing free gas in its volume. The larger the relative volume of the vapor-gas zone of HCA V V^V/V^Σ, the more NCG accumulates in it, the lower the concentration of dissolved gas in the liquid flow at the pump inlet.

The accumulation of NCG in the vapor-gas zone of HCA leads to a mismatch between the measured pressure and the saturation pressure, determined by the temperature in the HCA – ΔP. Table 1 and Fig. 4 show the calculated and experimental values of the pressure mismatch in the HCA. With increasing molar concentration, temperature, and during the transition from single-phase to two-phase mode, the pressure mismatch ΔP increases. The greatest influence on the value of ΔP is exerted by the value of the relative volume of the vapor-gas zone V^V/V^Σ. The smaller this ratio, the steeper the straight line $\Delta P_{cal}=f(m_{2x})$. This value in our study took the following values: V^V/V^Σ=0.25...0.4. The pressure mismatch ΔP becomes smaller with increasing volume of the HCA vapor-gas zone. The maximum ΔP observed in experiments was ~1.4 bar.

In order to accurately maintain the guaranteed cavitation reserve or boiling point of the coolant in cold plates, the pressure in the system must be regulated by controlling the temperature in HCA. The accumulation of NCG leads to the need to adjust the pressure or NPSH control program by up to 2.5 K.

The presence of NCG reduces the overheating of the cold plate during the onset of boiling and reduces the effect of hysteresis on the thermal load. These results are shown in Fig. 6, 7. This result qualitatively correlates with the data of [11, 12]. This effect of NCG on hysteresis in terms of thermal load can be explained by the effect of the partial pressure of the dissolved gas on the critical radius of viable vapor bubbles.

The experiments did not reveal a clear influence of NCG on the heat transfer coefficient at developed boiling.

Table 3 gives the experimental and calculated values of the heat transfer coefficients for 4 cold plate of different designs at different concentrations of NCG. The same contradictory result follows from our review of the literature [11, 12]. In cold plate with different designs of the evaporator channel, the experimental heat transfer coefficient could remain unchanged or change by ±25 % with an increase in NCG to m_{2x}=0.075. It is likely that the influence of NCG on heat transfer manifests itself in different ways on different surfaces of the cold plate. It is worth noting that the experiments to determine the experimental heat transfer coefficient had a fairly large methodological error, which is estimated at at least 15 %.

A study of the influence of NCG on the onset of pump cavitation shows that the required cavitation reserve increased by ~1.5–2.5 K with an increase in the molar concentration of dissolved NCG at the pump inlet to $4.5 \cdot 10^{-4}$ (Fig. 8 and Table 4). This result correlates with the data from [14]. If the pressure in the loop is regulated by the value of the cavitation reserve, then when NCG accumulates, it is necessary to adjust the control program.

Visual observations showed that there were no free gas bubbles in the liquid under stationary conditions at the inlet to the cold plates. In the adopted design of evaporators in the form of tubes with a diameter of 7 mm, blocking of the heat transfer surfaces is impossible, even in the presence of bubbles of free NCG.

Work [2] states that it is necessary to install a free gas trap in front of the pump. If under a two-phase operating mode there is no free gas at the pump inlet, then areas with vapor-gas flow still appear in the evaporators due to the boiling of part of the coolant with dissolved gas. In the condenser, the steam condenses, and the gas again dissolves in the stream of supercooled liquid before entering the pump. But it takes some time to dissolve. It was shown in [6] that individual bubbles of free gas can persist after the condenser, right up to the entrance to the pump.

Free gas can also appear at the pump inlet and when there is a sudden change in thermal load. In satellite thermal management systems, this is practically impossible due to high thermal inertia.

The solubility of gases in ideal solutions of low concentration increases with decreasing temperature. Since in the HCA the liquid is in a state close to saturation, and in the loop upstream of the pump the liquid is necessarily supercooled, the liquid in the loop has some potential for gas dissolution. During radiolysis, the concentration of NCG in the loop may increase. But due to fluctuations and continuous mass transfer between the HCA and the loop, the concentration of NCG in the liquid zone of the HCA and in the loop under a stationary mode is leveled out. During fluctuations, portions of cold liquid with an increased content of NCG will flow from the loop into the HCA, warm up, and gas will be removed from them into the vapor-gas zone of the HCA. And the portions of heated liquid leaving the HCA will be depleted of dissolved gas. Thus, this mass transfer mechanism will act as a «pump», pumping excess NCG from the loop to HCA. The HCA actually performs the function of a gas trap, the effectiveness of which is determined by the volume of the vapor-gas zone: the larger the volume, the better the NCG is separated.

As noted above, if there is insufficient time for complete dissolution of NCG after the condenser, free gas bubbles can enter the pump inlet. But, if there is a filter in front of the pump with a capillary seal that does not allow a large amount of free NCG to enter the pump, then the bubbles will be captured by the filter and will certainly dissolve over time. Therefore, the filter, with proper design, can serve as an additional «gas trap» [17]. The free NCG trap filter installed in front of the pump plays the role of a «separator» and «solvent», but not a «storage» of free NCG, so its volume can be small. The main gas trap, which ensures the localization of most of the free NCG, is the vapor-gas zone of HCA.

In the experimental loop, a standard mesh filter with a cell of ~0.1 mm was installed in front of the pump; there was no special gas trap at the pump inlet. In the experiments conducted, no problems with the operation of the pump due to the presence of free gas bubbles at the inlet were observed.

Limitations on the use of the results of this study include the following:

– during the radiolysis of ammonia, a non-condensable gas appears, consisting of moles of nitrogen and ammonia in a ratio of 1:3. In this study, pure nitrogen was used as the NCG;

– in the current paper, all results are represented in the form of dependences on molar concentration. It is known that the Henry coefficients for nitrogen and hydrogen are comparable in magnitude. The experiments were carried out at a molar concentration of nitrogen significantly higher than predicted. Therefore, the conclusions of the paper can be extended to the real composition of NCG;

– the experiments were carried out in a system with a fixed geometric volume of the HCA and loop. The ratio of the volumes of the system elements corresponded in order of magnitude to the standard 2PMPL. The work shows that the main influence on the pressure mismatch in the HCA, the distribution of NCG, and other parameters of the system is exerted by the relative volume of the vapor-gas zone in the HCA (V^V/V^Σ). As the relative volume decreases, the pressure mismatch in the HCA and the concentration of dissolved gas in the liquid increase. Therefore, these research results, at least in qualitative form, can be extended to other systems with a significantly different relative volume of the vapor-gas zone in HCA;

– when calculating the concentration of gas in free and dissolved form, the thermodynamic model of «ideal solutions» was used, which is strictly valid at a very low concentration of dissolved gases and low vapor gas pressure in HCA. Our work shows that in the coolant temperature range T_{HCA}=35...55 °C up to a concentration of dissolved gas in the liquid of $5.3 \cdot 10^{-4}$ mol nitrogen/mol mixture, the model satisfactorily describes the experimental data. At high coolant temperatures and NCG concentrations, additional experimental verification of the adequacy of the model will obviously be required.

Further development of this area of research is possible when using other heat carriers in the loops, for example, various freons.

7. Conclusions

1. The distribution of NCG in the heat transfer loop in free and dissolved form, the magnitude of the mismatch between the measured pressure and the saturation pressure in HCA can be calculated using a validated thermodynamic model of «ideal solutions». With the amount of NCG in the loop up to $m_{2x} \approx 0.075$ mol nitrogen/kg ammonia, the concentration of dissolved gas in the liquid in the studied range of parameters was no more than $5.3 \cdot 10^{-4}$ mol nitrogen/mol mixture, and the pressure mismatch was observed up to 1.4 bar.

Most of the NCG mass accumulates in the vapor-gas zone of HCA. The HCA can perform the function of the main «gas trap»; the larger the volume of the vapor-gas zone, the better. A filter with a small volume capillary seal installed in front of the pump could help trap and dissolve free gas.

2. It was experimentally determined that the presence of NCG reduces the overheating of the device when it is turned on due to the phenomenon of hysteresis in terms of thermal load. Overheating to 18K was observed in the degassed heat carrier. In the presence of NCG in the loop m $m_{2x}\approx$0.05...0.075 mol nitrogen/kg ammonia, the concentration of dissolved gas in the liquid is up to $x_2^L\times10^4\approx$3...5 mol/mol of the mixture – there was no overheating.

3. The presence of NCG has an ambiguous effect on the intensity of heat transfer during developed boiling of ammonia in cold plate of various designs, changing the heat transfer coefficient in cold plate of different designs by ±25 %.

4. With an increase in the amount of NCG in the loop to 0.075 mol nitrogen/kg of ammonia, the molar concentration of dissolved NCG at the pump inlet to $4.5\cdot10^{-4}$ mol/mol of the mixture, the required cavitation reserve increased by ~1.5...2.5 K compared to the degassed liquid.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to this study, including financial, personal, authorship or other nature that could affect the study and its results reported in this paper.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when preparing this manuscript.

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