TWO-PHASE THERMAL CONTROL LOOPS FOR CRYOGENIC TEMPERATURES

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Abstract

The the calculated analysis of traditional LHP designs with various working fluid for conditions of cryogenic temperatures is presented. On the basis of the received results, and also the literature analysis, the new two-phase loop design having the following basic differences is offered: 1 – application of auxiliary evaporator for startup from supercritical state, 2 – absence of usual reservoir or compensation chamber. For calculation dynamic processes at startup of two-phase cryo-loop the mathematical model is proposed, examples of calculations are given. The experimental breadboard is created and his tests results are submitted in paper. Results of calculations and experiments confirm serviceability of the offered device.

KEYWORDS

Loop heat pipe, Cryogenic temperatures, Overcritical parameters, LHP startup, Additional evaporator, Modeling, Experimental testing

INTRODUCTION

In cryogenic devices of both on-ground and space application there is a problem of ensuring heat connection between thermally controlled unit and radiator or cryogenic cooling machine. The method of heat transmission via heat conductivity is used when the heat gains and distances between the thermostatting object and cryogenic cooling machine are small. Such method of heat connection ensuring is reliable and made a good showing in practical experience. However it can not be used in some important practical cases:

1. Great distance between thermally controlled unit and cryogenic device (1 meter and more).
2. Great heat load (1 W and more).
3. Diode heat connection.
4. Mechanical decoupling in order to eliminate vibration. It is important for the thermostabilization of the sensitive elements of the optical devices.

Different one-phase and two-phase convection thermal control systems are used to meet the set requirements. Application of autonomous thermal control systems on base of two-phase loop with capillary pump (CPL) or loop heat pipe (LHP) is of particular interest.

WORKING FLUID SELECTION

Proper working fluid is important for good LHP operation. Currently the most prevailing parameter of the working fluid efficiency for application in two-phase loops with capillary pump is the complex parameter offered by Neil Dunbar $\frac{\rho \sigma r^{1.75}}{\mu^{0.25}}$, where r - heat of vapor generation, σ - surface tension, ρ and μ - density and viscosity of vapor.

In accordance with fig. 1 the temperature range of each working fluid efficient use is quite narrow. The working fluids with high efficiency in the field of cryogenic temperatures have low critical temperature.

Therefore the liquid phase of the working fluid under the storage conditions is missed and it is impossible to start LHP in the ordinary mode by applying heat power to the evaporator. The working fluids with liquid phase at the storage temperature have low efficiency in the field of cryogenic temperatures.

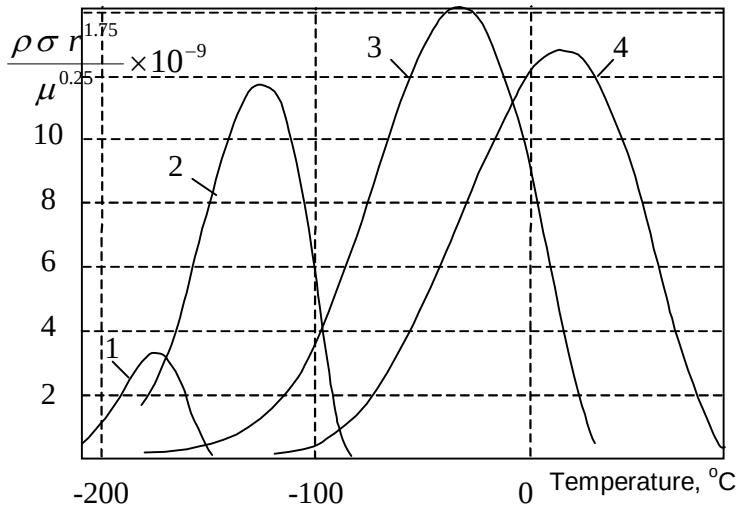

Figure 1. Dependence of working fluid efficiency on temperature. 1 – nitrogen, 2 – methane, 3 – ethane, 4 – propylene.

ANALYSIS OF POSSIBLE APPLICATION OF ORDINARY LHP FOR CRYOGENIC TEMPERATURES

Fig. 2 shows the example of the ordinary LHP calculation parameters if working fluid is ethane. It is impossible to maintain LHP operation ability at the temperature of less than –100°C although the freezing temperature of ethane is –183.3°C. It is caused mainly by the significant decreasing of the value $\left(\frac{dp}{dT}\right)$ in the field of low temperatures and consequently leads to increasing of temperature difference and heat flow between the evaporator and compensation chamber. Therefore the more subcooling rate of the liquid is needed that leads to the condenser flooding.

The value of methane $\left(\frac{dp}{dT}\right)_s$

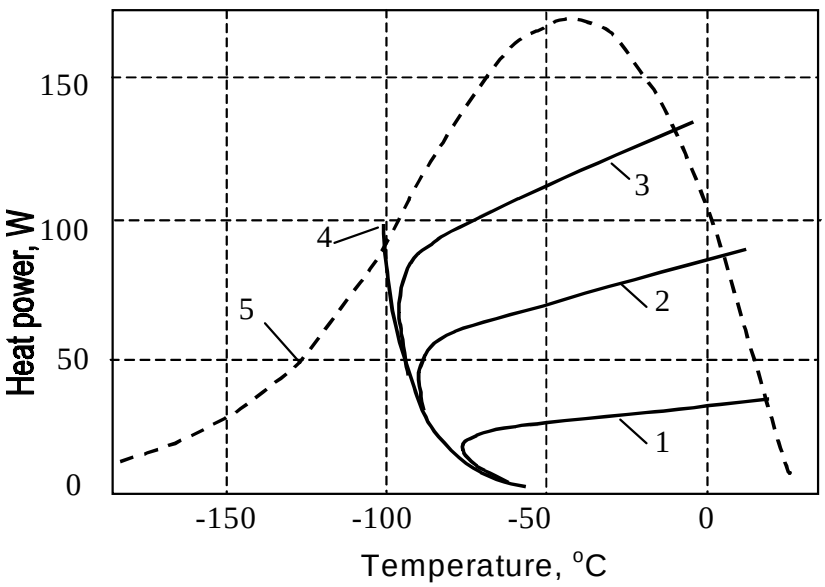

Figure 2. LHP calculation parameters at the different values of external heat transfer coefficient on the condenser, W/(m^{2}K): 1 – 20, 2 – 50, 3 – 80, 4 - ∞. 5 – maximal heat power. Working fluid – ethane.

at cryogenic temperatures is much greater than the value of ethane (more than 50 times at the temperature – 120°C). Use of methane under the same conditions allows to ensure significantly low temperatures (see Fig. 3). However under the normal conditions methane is in supercritical condition. Therefore special procedure of LHP startup is required: the additional system of preliminary evaporator cooling to the temperature below critical one is needed.

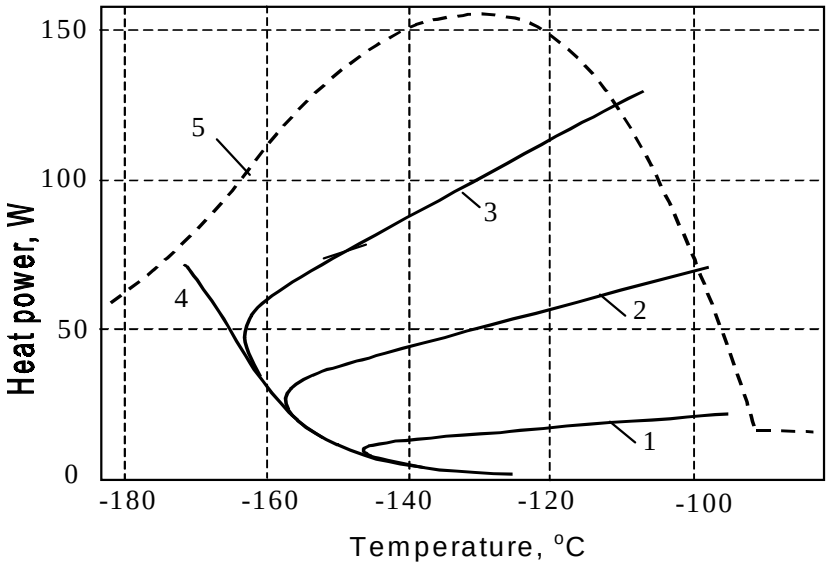

Figure 3. LHP calculation parameters at the different values of external heat transfer coefficient on the condenser, W/(m^{2}K): 1 – 30, 2 – 100, 3 – 200, 4 - ∞. 5 – maximal heat power. Working fluid – methane.

NEW LHP DESIGN FOR CRYOGENIC TEMPERATURES

The analysis shows that CPL or LHP operation under cryogenic conditions has some specific peculiarities uncharacteristic for CPL or LHP ordinary operation. Working fluid is usually in supercritical condition before LHP startup. The lack of working fluid liquid phase excludes the direct startup of thermal control system without its preliminary cooling.

1. LHP is usually started up not by evaporator heating but by condenser cooling.
2. In cryogenic temperature range working fluids properties essentially differ from their properties at normal conditions. First of all this phenomenon is displayed in low values of vapor density and $\left(\frac{\mathrm{d}p}{\mathrm{d}T}\right)_s$.
3. Strength aspects should be in the limelight because of high values of pressure in LHP at normal temperature.
4. It is necessary to solve the problem of heat gains to the liquid line and possible boiling of working fluid in the liquid line.

Taking into account the reasons mentioned above the requirements made to the design and layout of the cryogenic units are not the same made to the ordinary LHP and CPL. New design solution is needed for cryogenic loops. In papers [ ] there are some design solutions for cryogenic two-phase loops. Usually the have two reservoirs – “cool” and “hot”. The startup procedure of these loops is complicated and prolonged. Some design versions are offered in the present paper. The main peculiarities of such versions are the presence of the auxiliary evaporator attached to the main condenser, lack of the hot volume compensator, combining of the cool volume compensator and main condenser.

Fig. 4 shows the layout of two-phase loop with the capillary pump that allows to perform startup of two-phase loop from the supercritical condition of the working fluid. The peculiarities of the layout are as follows:

- presence of the additional auxiliary evaporator and condenser;
- lack of compensation chamber on the main condenser;
- combining of the volume compensator and main condenser.

The layout includes the main evaporator 1, directly attached to the cooled object, vapor line 2, main condenser with the volume compensator 3, auxiliary evaporator 4, auxiliary condenser 5, condenser line 6. Heat rejection from the condensers 3 and 5 is performed via radiator 7.

To cool the main evaporator 1 and perform the two-phase loop startup the liquid generated in the condenser should reach the main evaporator. Therefore LHP is supplied with auxiliary evaporator 4. Vapor enters the auxiliary condenser 5 where it is condensed. When heat is applied to the evaporator 4 and sections of condenser 3 and 5 are cooled the condenser line 6 and evaporator 1 will be filled with liquid and gradually cooled. The heat flow should be applied to evaporator 4 not constantly but from the moment of the condenser filling with liquid and its necessary supercooling to the moment when the wick of the main evaporator is filled with liquid. The heat flow value on the auxiliary evaporator is about half as much than the heat flow applied to the main evaporator. During two-phase loop operation in a stationary mode the heat is not applied to the auxiliary evaporator 4, vapor is not generated and wick of the auxiliary evaporator works as a capillary lock.

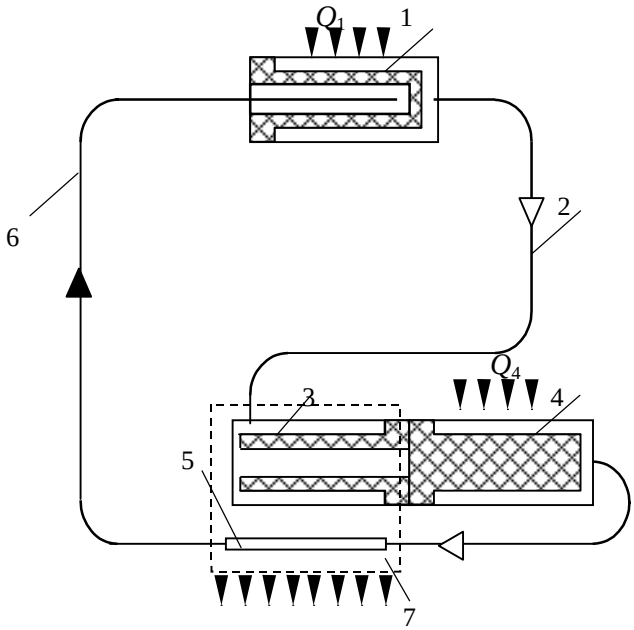

Figure 4. Layout of the supercritical cryogenic LHP

Design of the first cryogenic autonomous two-phase loops was quite complicated [1] – [3]. It consisted of five transport lines and two remote reservoirs – “hot” and “cold”. The design complexity and great number of the components decrease the reliability of the cryoLHP and increase the internal volume of the loop. The additional reservoir volume is needed to avoid the excessive pressure increase at the normal temperature. Due to the reasons mentioned above LHP mass, overall dimensions and total heat capacity are increased and startup of Cryo LHP is slowed down. Advanced LHP [3] – [5] consists of only three transport lines and two [3], [4] or one [5] reservoirs. The design described in [6] consists of only two transport lines and one external reservoir.

In the cryoLHP design described in the report only two transport lines are used and the remote reservoir is absent. The compensation chamber attached to evaporator and ordinary for LHP is also absent. The condenser works as a volume compensator and the volume of the condenser is slightly increased. The necessary value of the condenser volume is determined while carrying out some special calculations. The solutions mentioned above allowed to minimize the internal volume of the loop and work without the remote reservoir. The maximum pressure in the loop does not exceed 200 Bars under the storage conditions and at the normal temperature. The measures that were taken ensured the minimum mass overall parameters and minimum time of Cryo LHP startup.

MODELING OF CRYOGENIC LHP PARAMETERS

Operation principle of the described two-phase loop design differs from the operation of the ordinary LHP. Therefore the existing methods of LHP calculation are not used for the described design. Two mathematical models are developed for calculation of the parameters. The first one describes the stationary operation of the device. It is purposed for determination of geometrical dimensions of the device components, mass of the working fluid in the loop and maximum possible pressure increase. The model allows to calculate the pressure loss in each section of the loop during the working fluid movement and determine the maximum heat power of the main evaporator by the condition of equality of total pressure loss in the loop and capillary pressure.

In accordance with the calculation results the maximum heat power is 65W when the operation temperature is minus 130^0C and working fluid is methane. Maximum pressure at the storage temperature of 20^oC does not exceed 160 Bars**.**

In cryogenic loops the issue of minimization of internal volumes of components, filled with working fluid at operating modes, is of vital importance. This results from reducing maximum possible pressure of working fluid at LHP non-operating condition and, as a consequence, from decreasing the device mass.

The calculation results have shown that the liquid line should not be heat-insulated at small values of its diameter or any special additional cooling systems should not be applied. It is more efficient to neutralize heat gains at the expense of additional overcooling of working fluid in the condenser as well as decreasing of heat gains due to reducing the blackness rate of the condenser line surface.

The compensation chamber, traditional for LHP, becomes unnecessary since as LHP starts up by the condenser cooling. The basic condenser manufactured in a special way can be applied as a volume compensator. Calculations and structural development of various modifications of equipment show that it is always possible to develop the design where the working fluid pressure does not exceed 200 bar and strength margin is no less than 2.

The dynamical processes of the LHP startup are described in the second model. Cooling period of the main evaporator before the loop startup is also determined in the second model. The calculation is based on the equation of thermal balance for the loop component

$$m_i c_i \frac{dt_i}{d\tau} + r\frac{dm_i}{d\tau} = Q_i \tag{1}$$

Density of the vapor phase at any moment can be determined by the equation:

$$\rho'' = \frac{m_\Sigma - \sum m_i}{V_\Sigma - \sum \left(m_i / \rho'\right)} \tag{2}$$

where m_Σ - charging mass of working fluid, m_i - mass of working fluid in i-component of the loop, V_Σ - complete internal volume of cryoLHP.

By the obtained value ρ'' the saturation temperature t_s can be determined. If the current temperature of the loop component t_i is more than t_s in the equation (12) $\frac{dm_i}{d\tau} = 0$, otherwise $\frac{dt_i}{d\tau} = 0$.

Value of Q_i is determined by the type of the loop component and conditions of heat exchange.

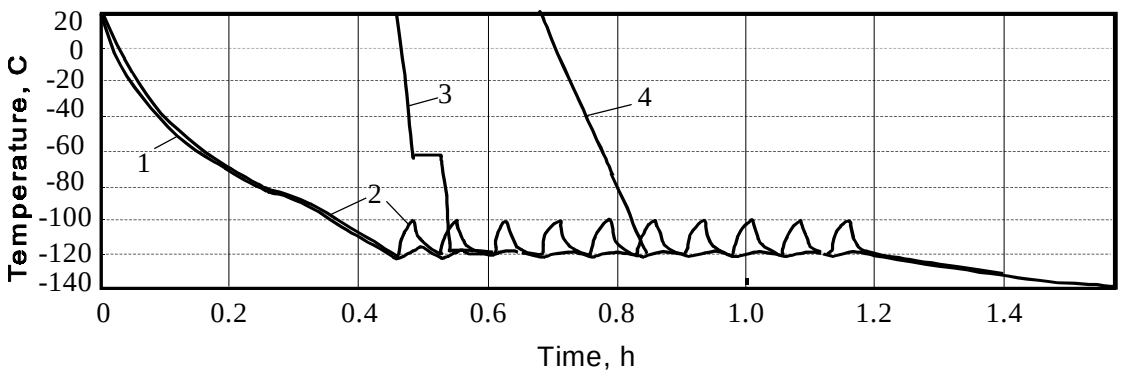

Figure 6. Cooling dynamics during the controlled startup of CryoLHP. 1 – basic condenser, 2 – additional evaporator, 3 – liquid line, 4 – basic evaporator.

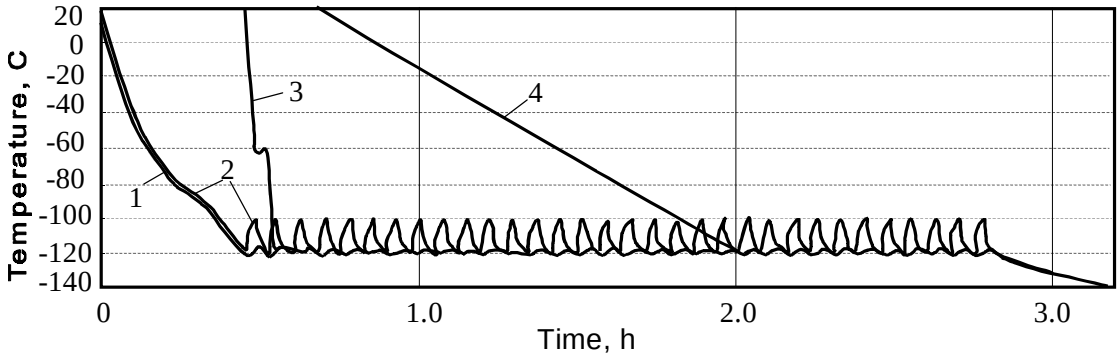

Figure 7. Cooling dynamics when mass attached to evaporator is 100 g. 1 – basic condenser, 2 – additional evaporator, 3 – liquid line, 4 – basic evaporator.

Solving the equations of type (1) for six main loop components (main evaporator, vapor line, main condenser, auxiliary evaporator, auxiliary condenser, condenser line) parameters of cryoLHP cooling can be obtained.

Power of the heater on the auxiliary evaporator and its turn-on time are the important parameters for the successful startup of the cryoLHP. Overheating of the working fluid in the auxiliary evaporator and its transition to the supercritical condition may be the results of uncontrolled heater operation under some conditions. Therefore the model provides for the calculation of cryoLHP startup in two modes:

- uncontrolled startup when the heater is turned on during the preset time from the moment of cooling start;
- controlled startup when the heater is turned on while the temperature of auxiliary evaporator

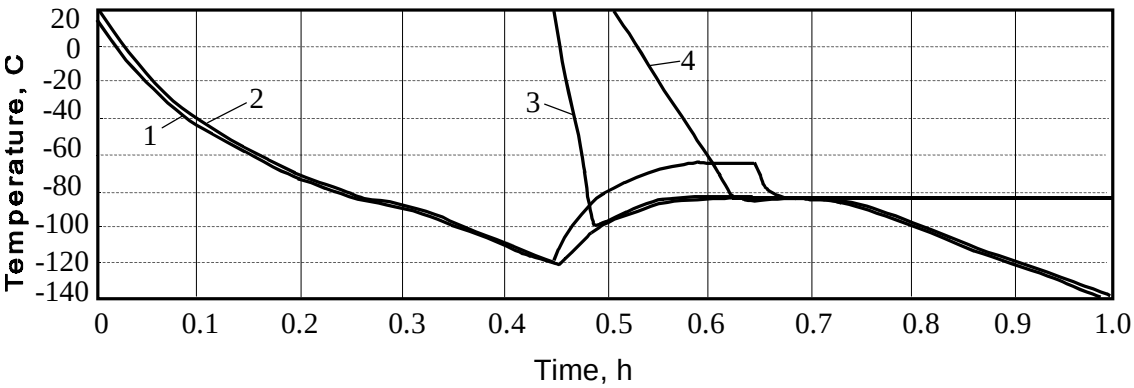

Figure 5. Cooling dynamics during the uncontrolled startup of CryoLHP. 1 – basic condenser, 2 – additional evaporator, 3 – liquid line, 4 – basic evaporator.

is decreased lower of set minimum value and turned off when the temperature of auxiliary evaporator is higher than the set value of turned-off temperature.

In both cases the heater is turned off when the main evaporator is filled entirely with the liquid.

It takes 0.7 of an hour to fill the main evaporator with working fluid liquid phase if cooling of the loop (from room temperature) is carried out in vacuum chamber by nitrogen screen with the temperature –195^{0}C and if uncontrolled turn-on of 2W-heater located at auxiliary evaporator takes place in 0.45 of

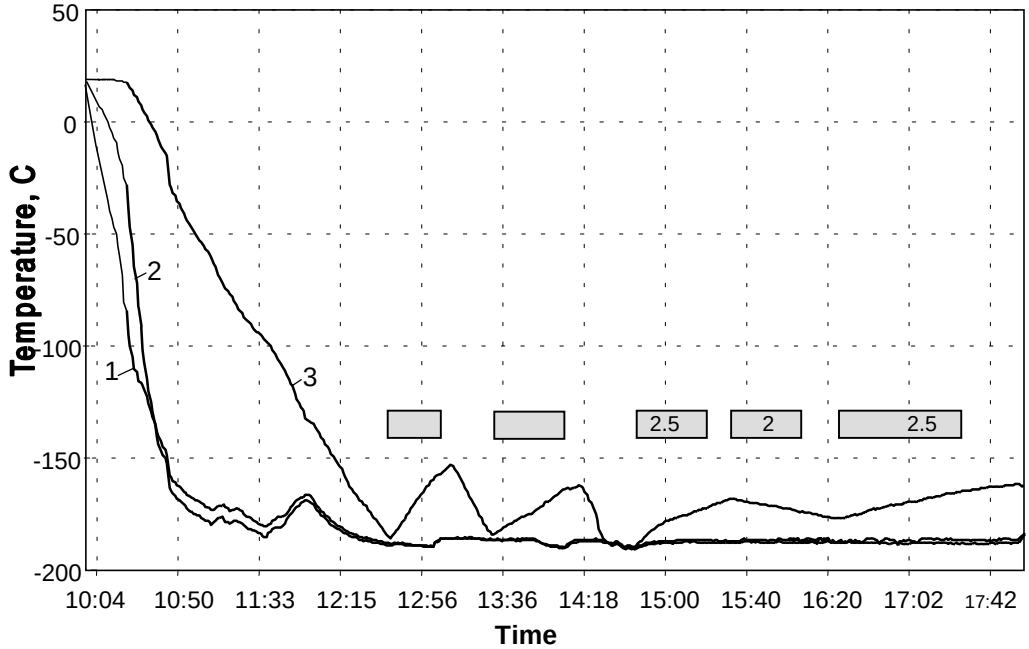

Figure 8. Experimental characteristics of nitrogen CryoLHP. 1 – condenser; 2 – additional evaporator; 3 – basic evaporator.

an hour after start of LHP cooling (see Fig. 5). Under the same conditions and controlled turn-on of the heater (the heater is turned on at the temperature of –120^{0}C and turned off at the temperature of –100^{0}C) the loop is cooled and the main evaporator is filled with liquid phase during 1.2 hour (Fig. 6). The heater "on-off" interval is 5 minutes. The heater is turned on for the half of this interval. The time of LHP cooling is by 1.7 times more under controlled startup. However such method of LHP startup is more reliable and makes impossible the working fluid overheating and its change to supercritical condition.

The results presented in Fig. 5 and 6 were obtained when no additional mass was attached to evaporator. If the mass of 100 g is attached to evaporator the time of LHP cooling and filling with liquid phase is increased up to 2.8 of an hour in case of controlled operation of the heater (see Fig. 7).

The calculations have shown that the auxiliary condenser cooling takes essentially less time than the primary one due to its smaller mass. As a whole the above-mentioned stages are commensurable for time when no additional mass is attached to the evaporator. The only exclusion is the very short stage of the liquid line cooling.

EXPERIMENTATION

To prove the theory mentioned above two cryogenic two-phase loops were manufactured in 2000 and 2001. The results of the last two-phase loop testing are presented on Fig. 8. Working fluid of cryoLHP is nitrogen. The tests were carried out in the vacuum chamber when condenser was cooled by liquid nitrogen heat exchanger with the temperature of 80K. Red color in abscissa axis (Fig. 8) shows turn-on of the main heater simulating the heat emission of the payload attached to evaporator. The 2W additional heater was turned on from 10.04 to 14.40. Startup cryoLHP is successful. In a stationary mode the CryoLHP stably removes 2 - 2.5 W of heat power.

CONCLUSION

1. The calculation analysis showed that it is impossible to maintain the operation temperature of evaporator below minus 100^0C in any conditions of heat rejection using traditional LHP design and working fluids having liquid phase at the normal temperature. The lower temperatures can be obtained using special loops where working fluid is in supercritical condition at the normal temperature.
2. CryoLHP design with the minimum quantity of components and minimum internal volume of the loop has been suggested. Such design allowed to have no remote reservoir. The maximum pressure in the loop does not exceed 200 Bars. Due to the measures that were taken such loops provide advanced mass and overall dimensions parameters. The LHP startup time is rather short.
3. Mathematical model has been created. This model allows to determine parameters of LHP components when maximum pressure does not exceed the preset value. The dynamics of CryoLHP cooling and startup can be calculated by using such mathematical model.
4. The experimental breadboard of CryoLHP with nitrogen as working fluid has been manufactured. The working ability of CryoLHP and truth of the calculated models were confirmed by the tests.

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