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Investigation of pulsations of the operating temperature in a miniature loop heat pipe

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Abstract

During the operation of miniature loop heat pipes (LHPs) one can observe pulsations of the operating temperature, which depend on the amount of the working fluid, the device orientation in the gravity field and the conditions of the condenser cooling. Intense pulsations, whose amplitude may exceed tens of degrees, arise from the lack of a working fluid in a LHP when a hot condensate or vapor bubbles periodically penetrate into the compensation chamber (CC) and act on the vapor phase in it, increasing its temperature and volume. Changes in the external conditions, for instance, the LHP arrangement in an unfavourable orientation or a more intensive cooling of the condenser with respect to the conditions for which the filling volume was optimal, also contribute to the initiation of intense pulsations of the operating temperature. In both cases one can observe redistribution of the working fluid between the condenser and the CC, as the result of which the liquid phase volume in the latter decreases and overshoots of vapor or a hot condensate there become possible.

Keywords: Loop heat pipe; Operating temperature pulsations

1. Introduction

Pulsations of the operating temperature, which take place in stable conditions of heat supply and removal, are a characteristic process inherent in some types of closed heat-transfer devices operating on the evaporation–condensation cycle. Such processes, in particular, may be observed in two-phase thermosiphons, in which temperature pulsations in the heating zone result from the boiling up of a working fluid at a reduced pressure [1,2]. In pulsating heat pipes the pulsation operating mode is the only one possible. In this case the amplitude of temperature fluctuations in them may reach tens of degrees and more [3]. When speaking about temperature pulsations, one should bear in mind that they are accordingly connected with pulsations of pressures and volumes of phases of the working fluid circulating in the LHP.

Similar phenomena have been discovered in loop heat pipes too. The first observations [4] showed that operating temperature pulsations arose with a decrease in the volume of a working fluid with respect to the optimum amount of it at which the LHP minimum thermal resistance was achieved. It should be mentioned that the amount of the optimum filling is influenced by the conditions of LHP operation, in particular, its orientation in the gravity field [5]. A more detailed study of the pulsation regime became possible relatively recently, with the advent of multichannel and high-speed means of measuring the temperature. With their help it has become possible to establish that the character of temperature fluctuations also considerably depends on the heat-load and the conditions of the condenser cooling [6], and the frequency and the amplitude of fluctuations may vary in a rather wide range [7,8].

The investigations conducted make it possible to differentiate three main types of the LHP operating temperature. The first of them is characterized by a low-amplitude (no more than 1 °C) and a high-frequency, which corresponds

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to the oscillations of the evaporating liquid front in the wick. The second type is also characterized by a low-amplitude of operating temperature pulsations, but their period is longer and reaches several minutes. In this case temperature fluctuations in the liquid line may be considerable, varying between the temperature values of the vapor and the medium that cools the condenser. According to investigations [7], such pulsations arise in the case that the interface in the condenser is situated close to one of its ends. The third type is distinguished by a high amplitude of operating temperature pulsations, which reaches tens of degrees, and a still longer period, which may be equal to tens of minutes. Such oscillations arise in the case that a massive heat source possesses a relatively low capacity, and the temperature of the condenser cooling is lower than that of the surrounding medium [8]. The amplitude and the period of oscillations decrease with increasing heat-load and heat-sink temperature.

Temperature pulsations were also observed in testing a miniature LHP with ammonia as a working fluid, whose condenser was cooled with running water [9]. The pulsation operating mode in this case took place in a limited range of heat-loads. The strongest temperature pulsations were observed in the liquid line at the exit from the condenser, where their amplitude reached 10 °C, but the amplitude of temperature pulsations in the vapor line in this case did not exceed 1 °C. The period of oscillations with increasing heat-load decreased from 100 s to 25 s and did not depend on the temperature of the cooling water.

Operating temperature pulsations, which are a rather wide-spread phenomenon accompanying the LHP operation, are not a fatal and inevitable factor limiting the practical application of these highly efficient heat-transfer devices. However, when the temperature of the object being cooled is to be maintained in a relatively narrow range, the rise of operating temperature pulsations may have negative consequences. A similar problem arose, for instance, during the development of a miniature LHP for the cooling system of the central processor of the portable computers [10]. Optimization of the volume of the LHP filling, which was realized for decreasing the device thermal resistance, resulted in the development of pulsation phenomena in the region of low values of the heat-load. Under certain external conditions their intensity was so high that it caused operating temperature pulsations with a considerable amplitude and even a crisis in the LHP operation.

The aim of the authors of the paper was the elucidation of reasons and conditions favorable to the origination of a pulsation mode of the LHP operation, their effect on the character of pulsations, and also the determination of means of preventing or weakening considerably pulsations of the operating temperature.

2. Description of the object and the methods of tests

For investigations use was made a miniature LHP, whose scheme is presented in Fig. 1. Ibidem one can see

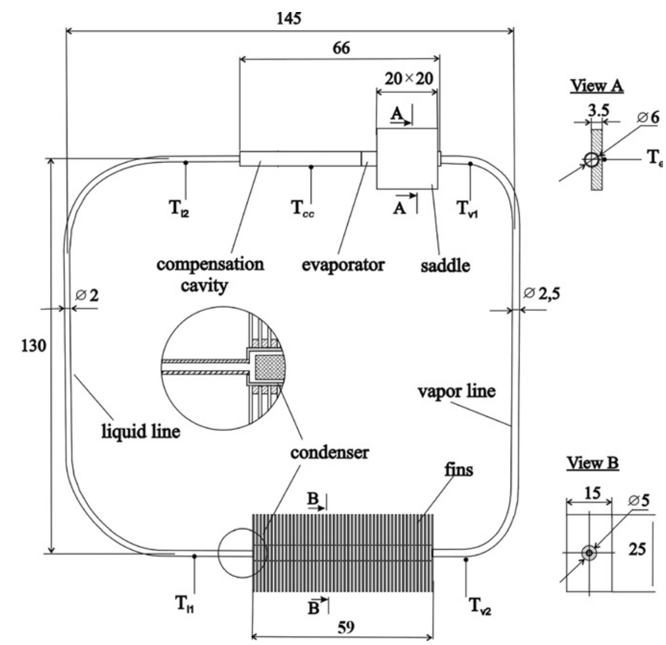

Fig. 1. Scheme of a miniature LHP.

the positions of thermocouples. The working fluid is ammonia. The device effective length was 230 mm. The structural material for LHP was stainless steel, with the exception of evaporator body, which was made of nickel. The wick, which had the porosity of 65% and a breakdown pore radius of 10 cm, was made of a sintered nickel powder. The evaporator was equipped with a copper thermal interface (saddle), the heat-load to which was supplied from an ohmic heater simulating the operation of a processor. The condenser was cooled with the help of a fan, which created an air-flow rate of 1.9 CFM at the outlet section of $60 \times 25\ \text{m}^2$ of the air line. The finning of the condenser consisted of 83 copper plates 0.2 mm thick.

The procedure of tests included measurements of temperatures at characteristic points of LHP with a successive stepwise increase and decrease of the heat-load. The interval of scanning of the indications of thermocouples was 10 s. The parameters of temperature pulsations, their location and the heat-load interval in which they were observed were determined in this case. The minimum heat-load value at which the LHP start-up was realized was 5 W. For the safety of tests the maximum heat-load was limited by the value at which the vapor operating temperature reached 80 °C.

The potentialities of the test bed made it possible to vary the amount of the working fluid in the LHP. The device to be tested was located in a horizontal plane or at an angle of 10° to it for compliance with the operating conditions of portable computers. For obtaining a more complete notion of oscillatory phenomena, tests were also conducted in other conditions, including those with a vertical orientation of the LHP plane and a more intensive cooling of the condenser by means of jet irrigation with thermostatted water.

3. Test results

3.1. Effect of the amount of the working fluid on operating temperature pulsations

Experiments on the effect of the amount of the working fluid (the filling volume) V_{ch} on the behavior of the operating temperature were conducted at the horizontal orientation of the LHP. The value of V_{ch} varied in the range from 1.04 cm^3 to 1.36 cm^3. Shown in Fig. 2 are time scannings of experiments which reflect heat-load dependences of temperatures at characteristic points of LHP for constant values of the filling. At a working fluid volume in the device equal to 1.28 cm^3 and more, temperature pulsations were observed at none of the device points in the whole range of heat-loads (Fig. 2a).

With a decrease in the filling to 1.20 cm^3 periodic temperature pulsations arose in the liquid line at heat-loads of 10 and 20 W (Fig. 2b). At 10W the period of pulsations was 190 s, and the amplitude of fluctuations of

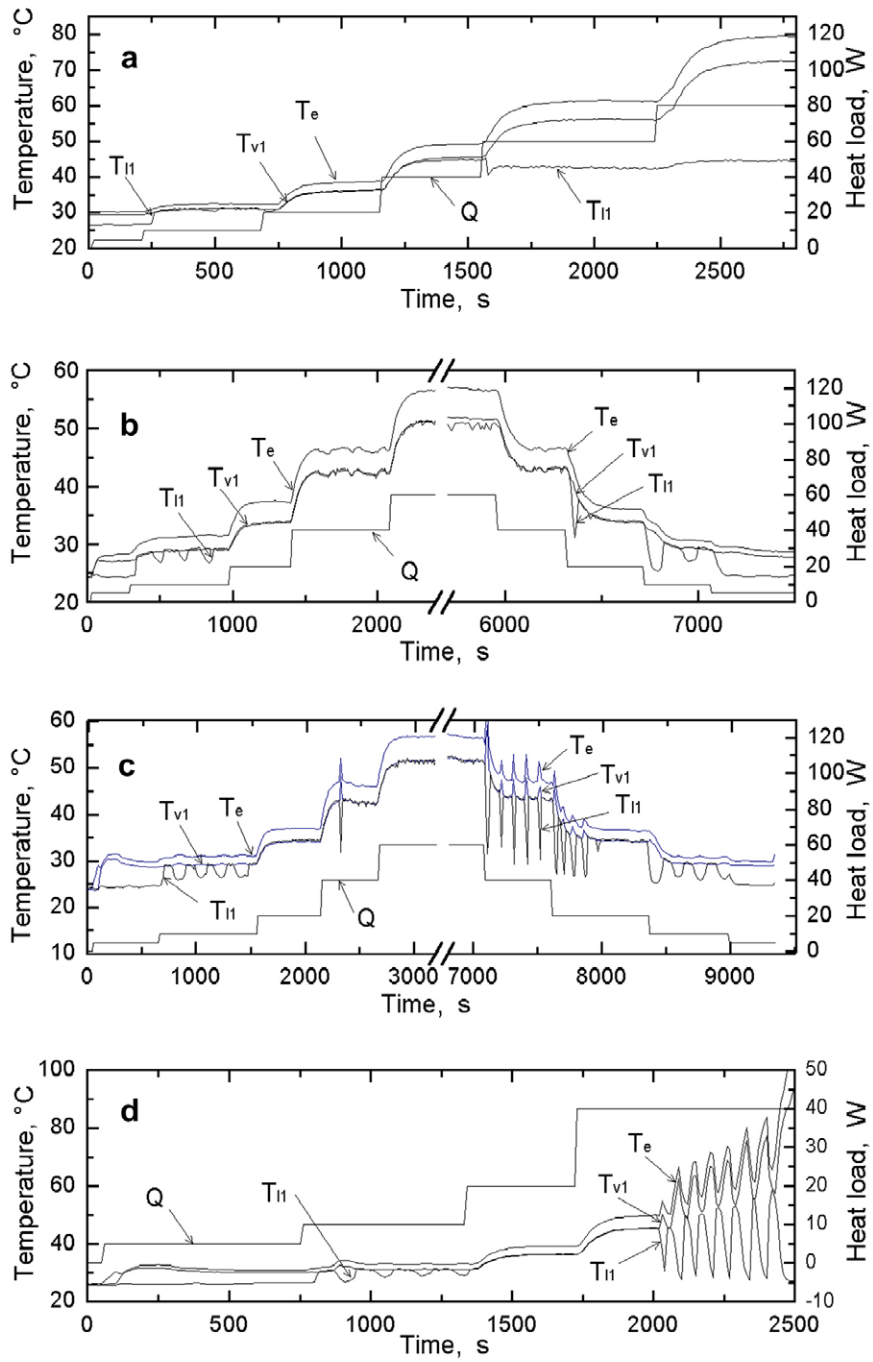

Fig. 2. Effect of the bulk of a working fluid V_{ch} on temperature pulsation's in LHP at horizontal orientation and air cooling of the condenser: (a) $V_{ch} = 1.28$ cm^3, (b) $V_{ch} = 1.20$ cm^3, (c) $V_{ch} = 1.12$ cm^3 and (d) $V_{ch} = 1.04$ cm^3.

the temperature at the exit from the condenser T_{11} and at the entrance into the evaporator T_{12} reached, respectively, 3 °C and 5 °C. In this case the temperature T_{12} itself varied between values close to vapor temperatures T_V and to those of the surrounding medium $T_{amb.}$ At a heat-load of 20 W temperature pulsations at the exit from the condenser disappeared, and the period and the amplitude of pulsations of T_{12} decreased end were equal, respectively, to 100 s and 2 °C. As is easy to see, the behavior of the vapor operating temperature T_V was scarcely affected by temperature pulsations in the liquid line. At a heat-load of 40W the operating temperature in stationary regimes had stable values, though high-frequency pulsations with an amplitude of no more than 1 °C could be observed on a liquid line.

When the filling bulk was reduced to 1.12 cm^3 (Fig. 2c), temperature pulsations spread to the vapor line. A single pulsation was observed in the section of increasing heat-load at 40 W, but the pulsation regime did not develop. However, at the section of decreasing heat-load at the same value of 40 W there arose periodic oscillations with a period of 102 s, the amplitude of operating temperature pulsations reaching 5 °C. With a further decrease in the heat-load pulsations in the vapor line disappeared, and in the interval from 10 to 20 W one could observe pulsations identical to those observed in the case of increasing heat-load.

At the smallest filling bulk of 1.04 cm^3 (Fig. 2d) the pulsations of the liquid temperature observed at a heat-load of 10 W disappeared after its rise to 20 W. But at the value of 40 W they appeared again, and not in a transition process but in conditions of the stationary state that had already set in. In this case the regime of pulsations of the vapor temperature T_V with a high amplitude which had previously (see Fig. 2c) manifested itself in the form of a single pulsation was realized at once. The amplitude of pulsations of increased monotonically and with time exceeded 20 °C. As a result, within 8 min after the beginning of pulsations their intensity reached such a degree that it caused disturbance of the LHP serviceability. It is of interest that the period of these pulsations (60 s) was almost half as big as that at the same heat-load with filling $V_{ch} = 1.12$ cm^3. The reason for the origination of new pulsations is, evidently, an overshoot of vapor or insufficiently cooled condensate into the compensation chamber (CC). They cause an abrupt increase in the temperature and the bulk of the vapor phase there, actuating by this the pulsation regime of LHP operation. In this case pressure pulsations in the flow of the working fluid corresponding to increasing pulsations of the vapor temperature might cause a break-down in the wick and the deterioration of the evaporation zone replenishment, which, as a result, caused a crisis in the LHP operation.

The present series of experiments has clearly shown that the reason for the pulsation operation mode is a smaller amount of the working fluid in the LHP than the optimum one. With a considerable shortage of the working fluid there arise intense pulsations of the operating temperature, which are capable of provoking a crisis in the LHP operation.

3.2. *Effect of the LHP orientation on operating temperature pulsations*

The main body of experimental data that reflect the effect of orientation on pulsation phenomena in the LHP was attained on a device filled with 1.20 cm^3 of a working fluid, and the condenser was cooled by an air flow. The device operation was investigated in two positions of its plane with respect to the plane of the horizon. In the first case the angle between them was equal to 10°, in the second to −90°. In each position of the plane the LHP was located in four different ways with respect to the gravity vector, as shown in Fig. 3.

Experiments conducted at a slope of 10° and filling volume $V_{ch} = 1.20$ cm^3 showed that with such a small change of the position the main characteristics of LHP operation remained the same as at the horizontal orientation. This concerns not only heat-load dependencies of temperatures, but also temperature pulsations. However, when the evaporator was located above the condenser, he crisis in the LHP operation connected with decreasing filling and the development of pulsations was observed even at a filling volume $V_{ch} = 1.12$ cm^3, whereas at the horizontal orientation this event took place at a smaller filling $V_{ch} = 1.04$ cm^3 (Fig. 2d). The character of development of the pulsation regime in both cases proved to be qualitatively the same. Temperature pulsations, which at heat-loads of 10 and 20 W were observed only in the liquid line, at 40 W extended to the vapor line. In this case their amplitude increased abruptly, which constituted to the crisis of the LHP operation.

At the vertical orientation of the LHP plane and filling $V_{ch} = 1.20$ cm^3 the regime of temperature pulsations was observed in positions "the evaporator above the condenser" (Fig. 3a) and "the CC above the evaporation zone" (Fig. 3b). The results obtained are presented in Fig. 4 for the ranges of heat-loads where pulsations were observed. In he position "the evaporator above the condenser", when the liquid returned into the evaporator overcoming gravity, at a heat-load of 10 W temperature pulsations arose not only on the liquid line, as in the case of the horizontal orientation, but also on the vapor line (Fig. 4a). The amplitude of pulsations of the operating temperature T_{vl} in this case exceeded 10 °C. With decreasing heat-load the pulsation character of the LHP operation at this heat-load was repeated. As is easy to see, in the section of decreasing heat-load at a value of 20 W one could also observe temporary, but possessing a considerable amplitude pulsations of the operating temperature. Despite the fact that the amplitude of the first pulsation was 28 °C, the LHP restored the stable character of operation, and 6 min later the oscillations abated.

In the position the "CC above the evaporation zone" the hydrostatic resistance of a liquid column is almost half as

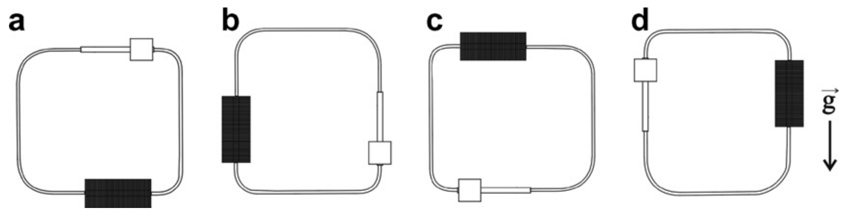

Fig. 3. LHP orientation with respect to the gravity vector.

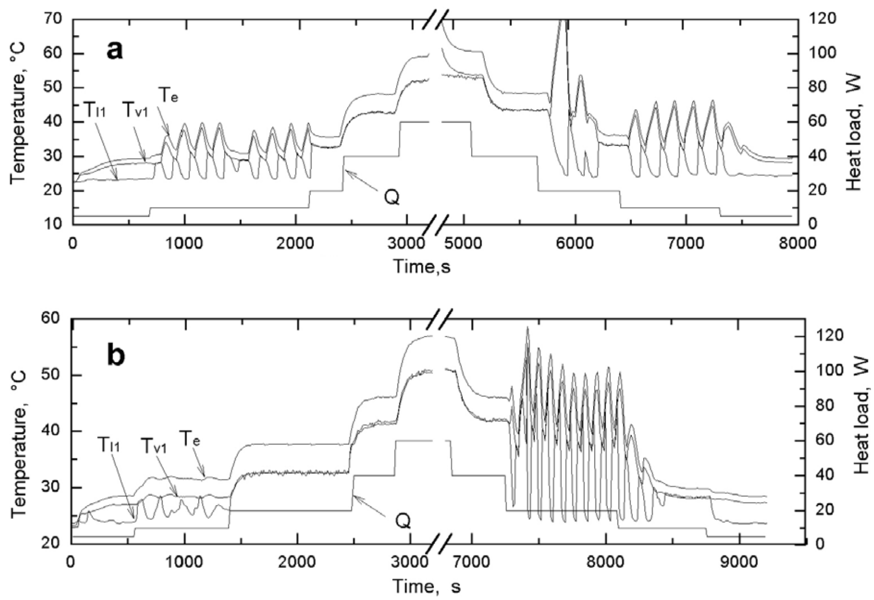

Fig. 4. Effect of orientation on pulsations of LHP temperature at air cooling of the condenser: (a) "evaporator above condenser" and (b) "CC above evaporator zone".

large as that in the position "the evaporator above the condenser". Therefore in the section of increasing heat-load one can observe only temperature pulsations in the liquid line (Fig. 4b), as in the case of horizontal orientation of the device. But in the section of decreasing heat-load at a value of 20 W there also arose temperature pulsations in the vapor line, whose amplitude of pulsations, for instance at the point T_{vl}, was 15 °C. However, even at a value of 10 W pulsations were not observed even in the liquid line.

In the position with the CC below the evaporation zone (Fig. 3d) the LHP operated properly only after a start-up at a heat-load of 30 W, as shown in Fig. 5a. Even a smooth decrease in the heat-load below 30 W resulted in an abrupt rise of the operating temperature and the depriming of the evaporation zone. In this case in the whole range of heat-loads temperatures at all LHP points remained stable. If the start-up was realized at a heat-load of 5 W (Fig. 5b), the temperature level of the device operation was very high, and the depriming of the wick began even at a value of 20 W. This could be judged by the decreasing heat-exchange intensity during evaporation. This circumstance may be connected with the fact that in such an LHP position the liquid level in the CC was lower than the wick, and the replenishment of the latter was not properly ensured.

When the condenser was positioned above the evaporator (Fig. 3c), temperature pulsations were observed only in the liquid line at low heat-loads of 5 and 10W. They were chaotic and had a relatively high-frequency (a period of less than 10 s), and their amplitude did not exceed 2 °C. Judging by the character of pulsations, one can assume that they were caused by the condensate flowing along the walls of the vapor and the liquid line. At higher heat-load values temperatures at all the LHP points were stable.

The experiments performed have shown that an unfavorable LHP orientation in the gravity field contributes to the initiation of considerable pulsations of the operating temperature. It should be noted that the depriming of the wick, which is observed in the position "the CC below the evaporation zone", and the temperature pulsations observed in other positions take place at the same heat-load values. Therefore it can be assumed that the initiation of considerable pulsations of the operating temperature at unfavorable LHP orientations is also connected with the shortage of a liquid in the CC. In this case the effect of gravity is expressed in the redistribution of the working fluid between the condenser and the CC, as a result of which the amount of a liquid in the latter decreases. The insufficient bulk of a working fluid in the LHP may aggravate this situation.

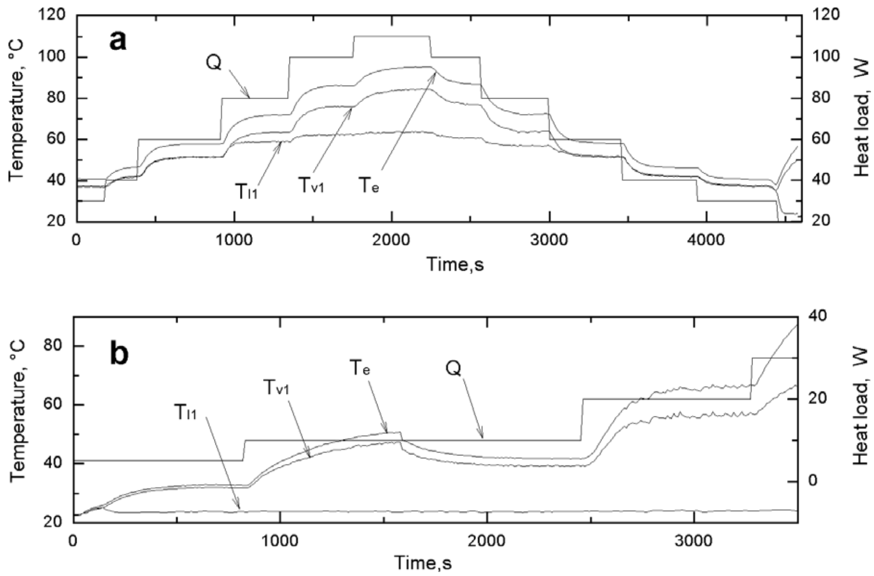

Fig. 5. Heat-load dependence of LHP temperatures at orientation "CC below evaporator zone" and air cooling of the condenser: (a) start-up at $Q = 30$ W and (b) start-up $Q = 5$ W.

3.3. Effect of condenser cooling conditions on operating temperature pulsations

The effect of condenser cooling conditions on operating temperature pulsations was investigated at the LHP horizontal orientation and an unchanged volume of the working fluid equal to 1.20 cm^3. The temperature of the surrounding medium during the experiments was in the range from 23 to 25 °C. Fig. 6 presents the results that reflect the dependence of pulsation phenomena on the temperature of the cooling water T_{cool}. At $T_{cool} = 15$ °C (Fig. 6a) the first pulsations of the operating temperature appeared at a heat-load of 40 W, and at 60 W they became periodic. The amplitude of pulsations of the vapor temperature increased with increasing heat-load and at a value of 80 W reached 15 °C. A crisis in the LHP operation began at a heat-load of 100 W, when the amplitude of pulsations became still higher.

When the condenser was cooled by water with the temperature of 25 °C (Fig. 6b), at first there arose pulsations in the liquid line at a heat-load of 20 W, but with the increase in the latter they disappeared. However, at a heat-load of 80 W the pulsation regime developed again, but now it was more intense and embraced all the LHP sections. The amplitude of pulsations of the vapor temperature T_{vl}, for instance, was in this case about 20 °C.

An increase in T_{cool} to 35 °C (Fig. 6c) led to the absence of pulsations in the vapor line in the whole range of heat-loads. One could only observe high-frequency pulsations (a period of less than 10 s) of the temperature in the liquid line at the exit from the condenser T_{11} with an amplitude of about 2 °C, characteristic of oscillations of vapor–liquid interface. On the whole the results of this series of experiments gave no way of revealing any definite dependence of the period of pulsations on the heat-load and T_{cool} as its value varied moderately in the range from 45 to 55 s.

The fact that on cooling by water with a temperature of 35 °C the LHP operated in a stable regime made it possible to achieve the highest heat-load value of 230 W for this device which gave a heat flux in the wick evaporation zone equal to 135 W/cm^2. It should be mentioned that this limitation was caused only by the heat-exchange crisis during the evaporation in the wick.

The condenser cooling conditions, as well as, the LHP orientation in space, affect the distribution of a working fluid between the condenser and the compensation chamber. Here we should note an observation concerning the case of air cooling of the condenser, which corroborates the effect of the intensity of the condenser cooling on the LHP operation. When the flow rate of the cooling air decreased, the pulsations observed at unfavorable LHP orientations disappeared. In this case even in the position "the CC below the evaporation zone" it was possible to realize a start-up and a stable operation of the LHP in the whole range of heat-loads, beginning with 5 W. This points to the fact that the degree of filling the CC with liquid at low heat-loads increases if the intensity of the condenser cooling decreases.

Thus, on the basis of experiments with water cooling of the condenser it may be asserted that a more intensive cooling of the condenser makes for the initiation of intense pulsations of the operating temperature, which may cause a premature crisis in the LHP operation.

It should be noted that the results obtained in this series of experiments are qualitatively different from the results of Ref. [9], where the condenser of a miniature similar-designed LHP was also cooled by water. Under changes of orientation and cooling water temperature no considerable pulsations of the operating temperature were observed

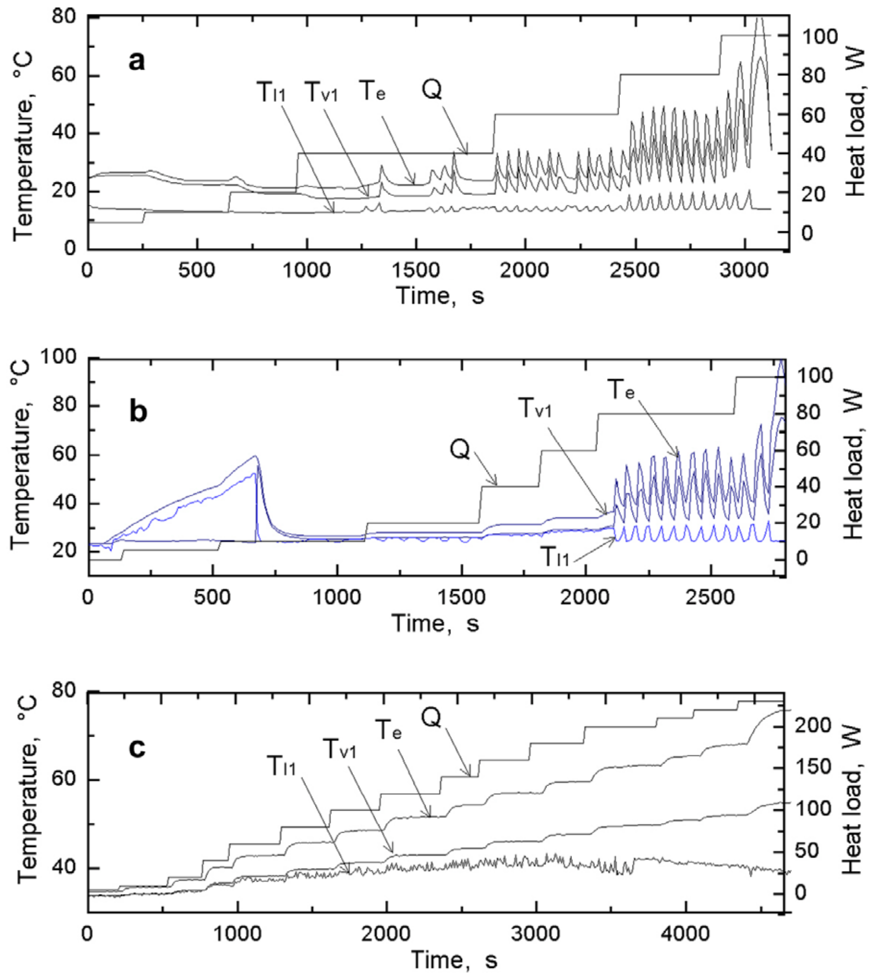

Fig. 6. Effect of cooling water temperature T_{cool} on temperature pulsations at LHP horizontal orientation: (a) $T_{cool} = 15$ °C, (b) $T_{cool} = 25$ °C and (c) $T_{cool} = 35$ °C.

there. The difference between the results is evidently caused not only by different amounts of the working fluid, but also by different realizations of means of water cooling determining the intensity of heat removal.

4. Discussion of the results

The study of the pulsation phenomena in the LHP makes it possible to assert that the basis for them is oscillations of the bulk of the vapor phase in the CC. These oscillations depending on their scale affect the behavior of the temperatures of all the LHP parts, including the operating temperature. The reason for the instability of the vapor bulk is the thermal action exerted on the working fluid in the CC by the evaporation zone, the condensate arriving at the evaporator and the surrounding medium.

Among the results obtained one can see all the three types of pulsations of the operating temperature corresponding to the suggested gradation by the characteristics of pulsations [7,8]. High-frequency pulsations with a low amplitude, typical of the first type, are observed, for instance, in experiments in which changes take place in the amount of the working fluid in the LHP (Figs. 2b and c), its orientation in space (Fig. 4) and the cooling water temperature T_{cool} (Fig. 6c). These pulsations are observed at both high and low heat-loads and may be accompanied by similar temperature pulsations in the liquid line (Fig. 6c). However, on the whole they do not affect the LHP heat-transfer characteristics. Pulsations of the second type also manifest themselves in all the series of tests (Figs. 2b, c and d, 4b, 6a), but at low heat-loads of 10–20 W. They are characterized by the presence of synchronous temperature pulsations on the liquid and the vapor line. In our experiments the amplitude of such pulsation T_v did not exceed one or two degrees, though the temperature pulsations in the liquid line were more considerable. The third regime is accompanied by intense temperature pulsations at all positions, including those in the compensation chamber, and may cause a crisis in the LHP operation. Such a regime is observed when there is a considerable shortage of a working fluid at the horizontal orientation (Fig. 2d), and also at unfavorable orientations (Fig. 4) and an intensive cooling of the condenser (Fig. 6a and b). However, as distinct from the well-known results [6–8], in our experiments intense operating temperature pulsations are observed not only at low but also at sufficiently high values of heat-load, causing a crisis in the LHP operation.

Experiments with different amounts of a working fluid in the LHP have shown that its shortage is one of the factors that initiate the pulsation operation mode. If there is little operating fluid, the section of the liquid supercooling in the condenser becomes smaller or disappears altogether, therefore the liquid entering the CC is hotter. Apparently, with a considerable shortage of a working fluid the share of the liquid phase decreases not only in the condenser, but also in the compensation chamber. In such a case there may be a vapor overshoot into the CC along the liquid line from the condenser. When a hot liquid or vapor arrives at the CC at regular intervals, oscillations of the vapor bulk arise there and affect, in particular, the behavior of the LHP operating temperature.

An unfavorable orientation contributes to the intense pulsations of the vapor line temperature. For instance, if at $V_{ch} = 1.20\ cm^2$ and the horizontal orientation of the LHP the pulsation regime manifests itself in the form of low-amplitude pulsations of the liquid temperature, in the case of unfavorable orientations one can also observe considerable pulsations of the vapor temperature. The reason for this is the effect of gravity, which causes redistribution of the working fluid between the condenser and the compensation chamber. As a result, the amount of the liquid in the latter decreases because part of it moves into the condenser or the liquid line.

At a more intensive cooling of the condenser, as well as in the case of an unfavorable orientation, one can observe redistribution of the working fluid in the LHP. But in this case the relation between the temperature of the medium cooling the condenser T_{cool} and the temperature of the surrounding medium T_{amb} becomes essential. These quantities determine the thermodynamic state of the working fluid, respectively, in the compensation chamber and in the condenser. If T_{cool} is below T_{amb}, then, all other things being equal, the amount of a liquid in the CC decreases as compared with the opposite case, where T_{cool} is higher than T_{amb}. In such a situation with a sufficiently small filling volume there may be overshoots of vapor or an insufficiently cooled condensate into the compensation chamber, which may provoke intense pulsations of the operating temperature. If T_{cool} is considerably higher than T_{amb}, the bulk of the liquid phase in the CC increases as the liquid is squeezed in there from the condenser. In an experiment at $T_{cool} = 35\ ^\circ C$ the compensation chamber was evidently completely filled with the liquid phase even at the start-up and remained in such a state with an increase in the heat-load up to the maximum value. Thus, in this case a necessary condition for the existence of pulsations, i.e. the presence of the vapor phase in the CC, was absent.

It is obvious that a similar situation with the distribution of a working fluid took place in the case of air cooling of the condenser when the heat removal intensity decreased. In this case the LHP operating temperature was sufficiently high even at relatively low heat-load values, and the vapor pressure was high enough for the CC to be filled with the liquid displaced from the condenser. Therefore temperature pulsations were not observed even when the LHP operated at unfavorable orientations. Thus, an increase in the temperature of the cooling medium or a decrease in the intensity of heat removal from the condenser prevents pulsations of the separating temperature. However, a consequence of their cessation is an increase of the temperature level of the LHP operation and, accordingly, an increase in its thermal resistance.

5. Conclusion

Tests of a miniature ammonia LHP have shown that its operation may be accompanied by temperature pulsations of different intensity depending on the amount of a working fluid, orientation and conditions of the condenser cooling. In particular, operating temperature pulsations are observed when there is a shortage of a working fluid in the LHP.

To ensure an LHP stable operation, the amount of a working fluid should be chosen with allowance for the external conditions in which the device service is expected. If they change, for instance, if the device orientation becomes unfavorable or the heat removal from the condenser is intensified, there may arise pulsations of the operating temperature. The action of these two factors on the LHP operation consists in redistribution of the working fluid between the condenser and the compensation chamber. In this case the bulk of the liquid phase in the latter decreases as compared with that observed during the LHP operation in nominal conditions.

Thus, on the basis of the investigations conducted it may be concluded that pulsations of the operating temperatures in an LHP are caused by both the general shortage of a working fluid in the device and the shortage of its liquid phase in the compensation chamber which is observed under certain external conditions.

The presence of pulsation phenomena is not a critical factor in the LHP operation. If it is impossible to increase the amount of a working fluid in the device, one can avoid temperature pulsations by means of increasing the temperature of the medium cooling the condenser or by decreasing the intensity of its cooling.

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