HYSTERESIS PHENOMENA IN FLAT-TYPE LOOP HEAT PIPE

by

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Testing of loop heat pipes showed that the heat-load dependence of the operating temperature was not always unambiguous. It may have hysteresis phenomena. The temperature hysteresis had a certain relationship with previous history of the power variation, and also related to the initial parameters of the loop heat pipes. It has been found that the temperature hysteresis of the loop heat pipes was related to the gas-liquid distribution in the compensation chamber which depended on the interaction between heat leak of evaporator and the reflux liquid from condenser. The temperature of the loop heat pipes evaporator rose with the gas phase in the compensation chamber increased.

Key words: *loop heat pipe, hysteresis phenomena, stability of two-phase flow, initial distribution of working fluid, heat leakage of evaporator*

Introduction

Loop heat pipe (LHP) is a high-efficiency heat transfer device with two-phase, it can transfer large amount of heat under small temperature difference and long distance conditions. The LHP was invented by Dr. Maydanik in Russia at 1972. A LHP therefore consists of an evaporator enabling the heat supply to the working fluid, a vapor transport line, a condenser transferring the heat from the working fluid to the ambient, a liquid transport line and a fluid reservoir, the so-called compensation chamber (CC). One of the most important features of LHP is its self-sufficient operating mode, based on capillary pumping in a porous wick structure integrated between the evaporator wall and the CC [1, 2]. The LHP are classified into two categories according to their evaporator shape: cylindrical evaporator LHP and flat-type evaporator LHP. Compared with the cylindrical LHP, the flat-type LHP of the same size has a stronger heat transfer capacity [3]. With the development of technology, LHP is developing towards miniaturization [4, 5], high heat flux [6, 7], for long distance [8, 9], anti-gravity [9, 10]. In addition to the heat dissipation of civil electronic devices, LHP also has broad application prospects in the field of spacecraft thermal control [11].

At present, the research on LHP mainly focuses on the porous wick structure of LHP [12], the cryogenic LHP [13], the operating characteristics of multi-evaporator LHP [14, 15], the instability of LHP [14, 16], *etc*. Wolf and Bienert [17] discovered that LHP has temperature hysteresis. The temperature hysteresis was identified by the fact that the operating temperature depends upon not only the imposed power but also the previous history of the power

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variation. Kaya and Ku [18] considered the hysteresis of capillary hysteresis, and the metastable state of the gas-liquid in CC and initial distribution of working fluid in the LHP were the sources of temperature hysteresis. Vershinin and Maydanik [19] studied temperature hysteresis of LHP, and the temperature hysteresis phenomenon of LHP were classified into three categories. The first type was the temperature hysteresis caused by the change in the amount of the parasitic heat flow that penetrates into the CC, which in its turn was a result of heat transfer hysteresis in the evaporation zone. In the second, temperature hysteresis was connected with the liquid metastable state, which leaded to a delay of formation of the vapor phase in the CC. The third type was related to the initial distribution of the liquid in the LHP, the temperature hysteresis occurred when LHP was started below a certain critical thermal load. Authors [20-22] experimentally studied the temperature hysteresis of the double reservoir LHP, and considered that the temperature hysteresis was closely related to the evaporator leakage heat.

The experiments showed that the temperature hysteresis of flat-type LHP was not only temperature different at the same heat load, but also the following new situations were discovered: first, under some working conditions, LHP operated stably at heat load step increased, but temperature oscillation occurred at heat load step decreased and second, the temperature of operated stably LHP suddenly increased or decreased, or occurred temperature oscillation.

The temperature hysteresis of LHP caused the temperature uncontrollable or instabilized, which affects the application of LHP for the heat dissipation of electronic devices that require precise temperature control. So it is important to study the hysteresis phenomena of LHP.

Experiment system

The experimental system is composed of LHP system, auxiliary heating system, environmental temperature control system and data acquisition system. Figure 1 shows a schematic diagram of a flat-type LHP system consisting of a flat-type evaporator with a 500-mesh stainless steel wire mesh (wire diameter 50 μm, 82 layers in total) porous core (shown in fig. 2), vapor line, air-cooled tube-fin condenser, and liquid line. All components except the porous wick are made of copper. The specific geometric parameters are shown in tab. 1. The working fluids (methanol with purity of 99.9%) were degassed prior to charging the LHP system. According to tab. 1, the internal volume of LHP can be calculated to be 31233 mm^3, and the working fluid filling rate of LHP is generally between 50% and 80%. If the fluid charge ratio is too low, wick dry-out is prone to occur with the increase of input power and induces an increase in the loop operating temperature. If the fluid charge ratio is too high, there may not be sufficient space for phase change [23]. The system vacuum is pumped to $3.0 \cdot 10^{-4}$ Pa before charging the working fluid, and then the working fluid is charged into the LHP. The temperature measurement system uses a Keithley-2700 data acquisition instrument to connect 12 copper-constantan *T*-type thermocouples to detect the temperature of the LHP. The temperature error of all thermocouples after calibration is ±0.2 °C. The position of each measuring point is shown in fig. 1. The auxiliary heating system is installed in a 40 × 30 × 35 mm copper block as a simulated heat source using two heating rods. A digital power meter with accuracy of ±0.2 W is used to measure and control the input power to the simulated heat source. The outer layer of the simulated heat source is wrapped with a thermal insulation material having a thickness of 10 mm and a thermal conductivity of 0.012 W/mK.

In the experiments, the LHP was operated at the elevation angle, θ, of 10°, 50°, and 90°, and the working fluid filling ratio, α, of 50 vol.%, 60 vol.%, and 70 vol.% in the cold mode. The procedure of tests included measurements of temperatures at characteristic points of the LHP with a successive stepwise 12 W increased and decreased of the heat load. The heat loads of start-up tests were from 12 W (heat-flux 1 W/cm^2) to 120 W (heat-flux 10 W/cm^2).

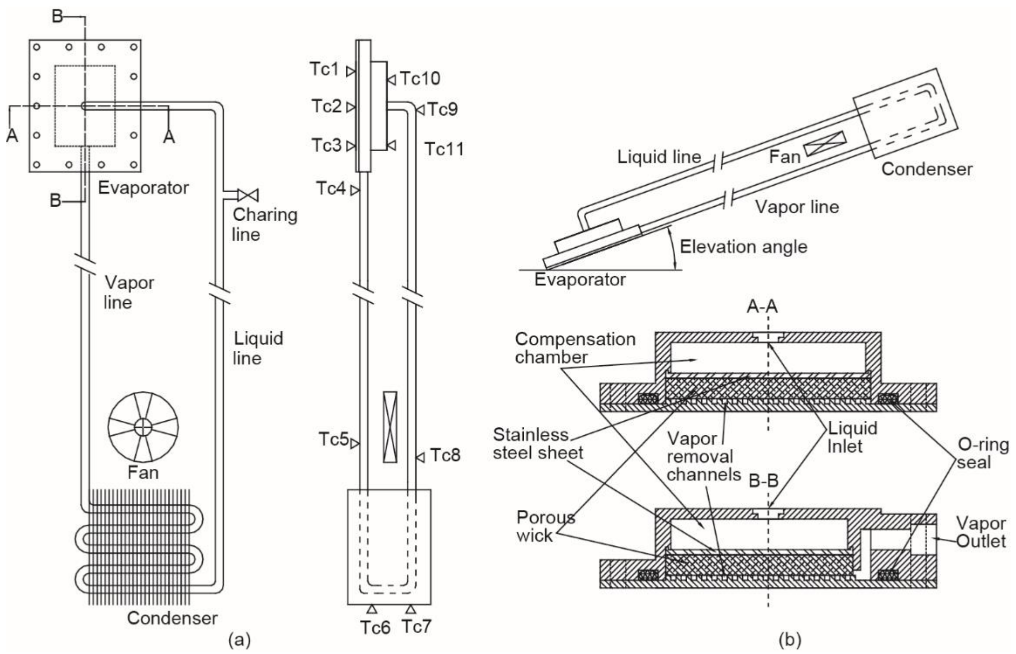

Figure 1. Schematics of the LHP; (a) top and side view of the LHP and the placement of the thermocouple points and (b) cross-section of the LHP evaporator

Table 1. Geometric characteristics of the experimental LHP

Evaporator	Active heated zone	Thickness [mm]	1.5	Vapor line	Diameter (O/I) [mm]	6/4
		Length/width [mm]	40/30		Length [mm]	320
		Groove thickness [mm]	1	Liquid line	Diameter (O/I) [mm]	6/4
		Fin size [mm]	1 × 1 × 1		Length [mm]	530
		Fin number	18 × 15	Condenser	Diameter (O/I) [mm]	6/4
	Wall	Thickness [mm]	1.5		Length [mm]	810
	Compensation chamber	Length/width [mm]	34.5/30		Fin thickness [mm]	0.05
		Height [mm]	6		Fin length/width [mm]	100/20
	Steely sheet	Thickness [mm]	0.5		Fan rotate speed [rpm]	3000
		Porosity	0.8	–		
		Length/width [mm]	36.5/30			
	Porous wick	Length/width/height [mm]		36.5/30/4		
		Material [L]	316	Parameter of mesh	500#, 82 layers	
		Wire diameter [mm]	0.05	Porosity	0.638	

Experimental results and discussions

Influence of the power variation history

Figures 2 and 3 showed the variable heat load operation characteristics of LHP at different working fluid filling rate and elevation angle. Figure 4 showed the temperature hysteresis of the evaporator wall of the LHP. The temperature of the evaporator wall was not only related to the heat load value, Q, but also Q-step up or Q-step down.

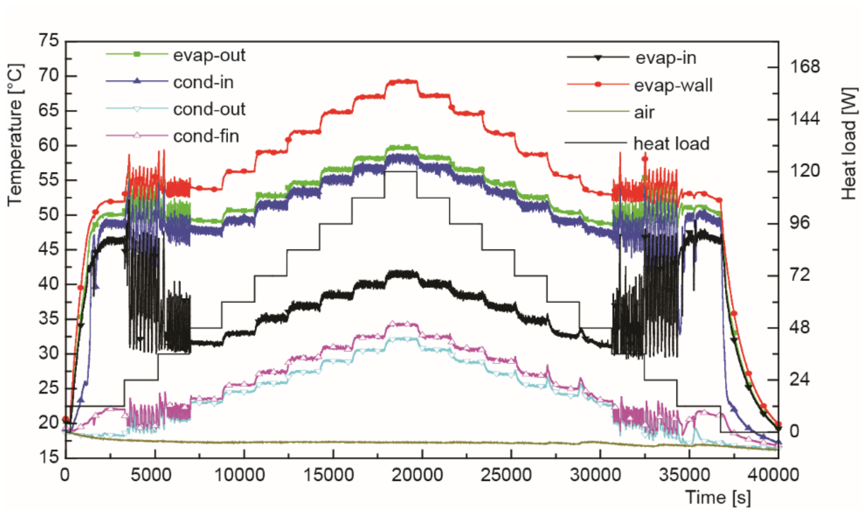

Figure 2. Performance tests of the LHP at power cycle at θ = 90°, α = 60 vol.%

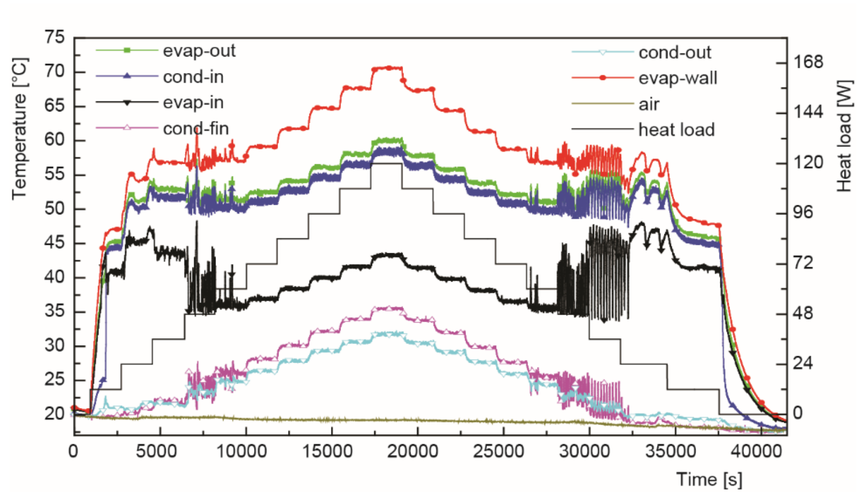

Figure 3. Performance tests of the LHP at power cycle at θ = 10°, α = 50 vol.%

As shown in fig. 4, that the temperature hysteresis of the flat-type LHP basically flowed the rules: when the heat load was large, the temperature of evaporator wall at Q-step up was higher than that of Q-step down, and as the heat load increased the differences become smaller. At the low heat load zone, the temperature of evaporator wall at *Q*-step up was lower than *Q*-step down.

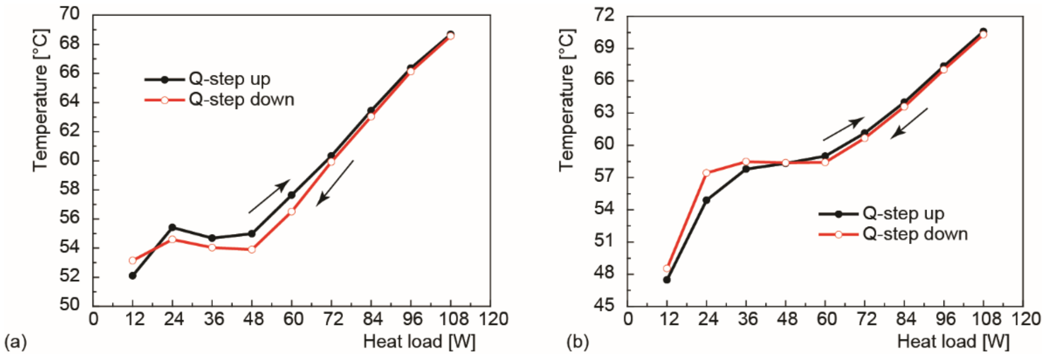

Figure 4. Temperature of evaporator wall at power cycle; (a) θ = 90°, α = 60 vol.% and (b) θ = 10°, α = 50 vol.%

The reason was that at the same heat load, the temperature of the LHP evaporator was mainly affected by the gas-liquid distribution in the CC. When the gas phase was large, it is not conducive to capillary rehydration and liquid reflux from the condenser. This caused the temperature of evaporator to rise. On the contrary, if the gas phase in CC was less, the porous wick replenishment and liquid reflux were facilitated, and the evaporator temperature was lower.

- As the heat load increase, more working fluid flowed back to the CC to inhibit the bubbles growth. On the other hand, the increase of the parasitic heat flow that penetrates into the CC promoted bubbles growth. With the heat load decrease, the liquid returning from the condenser reduced, the bubbles in the CC were tend to grow, but at the same time, the parasitic heat of the evaporator was also reduced, and the bubbles in the CC were tend to shrink. When the effect of the parasitic heat was greater than that of the reflux liquid, the gas bubbles in the CC increased, the porous wick supply was deteriorated, thereby causing the temperature of each part of the evaporator to be higher. When the reflux liquid was sufficient to suppress the growth of the bubbles, the evaporator porous wick supply was sufficient and the evaporator temperature was lower.
- At the large heat load, the evaporator stored more parasitic heat. When the heat load decreased, the evaporator released parasitic heat, which caused the hysteresis of the evaporation. As shown in fig. 2, when the heat load decreased, the temperature of condenser outlet rose slightly, indicating that the release of parasitic heat produced more bubbles. The reflux working fluid inhibited the growth of bubbles in the CC and improved the liquid supply of the porous wick. So that the temperature of the evaporator at *Q*-step down was lower than that of the *Q*-step up. When the heat load increased, the increase of evaporation had a delay due to the parasitic heat of the evaporator. The increase of the working fluid returning to the CC was delayed which lead to bubbles growth in the CC. The growth of the bubbles deteriorated the supply of the porous wick, and the temperature of each part of the evaporator was higher than that of *Q*-step down.
- At little heat load, the evaporator parasitic heat was less. When the heat load decreased, the evaporator and the porous wick released a little amount of heat. The increased return flow was not enough to inhibit the parasitic heat release in CC, thereby causing the bub-

ble to grow in the CC. As a result, the temperature of evaporator was higher. So, at the little heat load zone, the temperature of evaporator was lower at Q-step down than that of Q-step up.

- At an intermediate heat load, the release of the parasitic heat of the evaporator increased the flow rate of the working fluid which inhibited the growth of bubbles in the CC. On the other hand, the released parasitic heat caused the bubble to grow. When the two functions were equivalent, the final evaporator temperature was equal at Q-step down and Q-step up.
- As shown in fig. 2 and fig. 3, temperature oscillations occurred at some heat load, the temperature oscillation was usually more violent at Q-step down than Q-step up. The reason was that the release of parasitic heat promoted the temperature oscillation at Q-step down.

Influence of initial temperature

The experimental results showed that the initial temperature of the LHP also affects its final operating temperature, as shown in figs. 5 and 6. When the initial temperature was lower, figs. 5(a) and 6(a), the final operating temperature of the LHP was also lower. The main reason was that bubbles were easier to grow in CC at high initial temperature of the evaporator. The growth of the bubbles decreased the reflux of the liquid working fluid, resulting in the lack of liquid in the porous wick. This type of hysteresis phenomenon was obvious at the working fluid filling rate of 50%, it was not obvious at filling rate of 60% and 70%. High initial temperature not only resulted in high operating temperatures, sometimes it caused temperature oscillation, such as fig. 5(b).

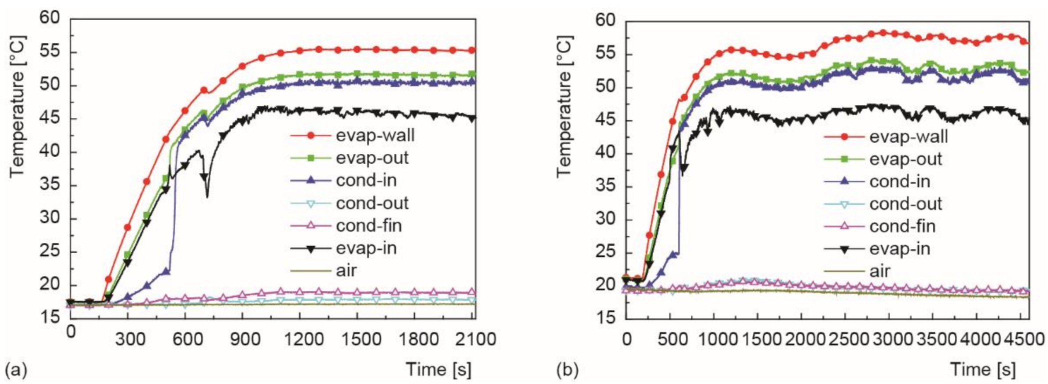

Figure 5. Start-up of the LHP, Q = 24 W, θ = 10°, α = 50 vol.%

Influence of gas-liquid metastable state

The hysteresis phenomenon of the LHP not only occurred at power cycle, but also occurred at some stable heat load, as shown in fig. 7. The temperature of the evaporator suddenly decreased when the operation reached stability. Figure 7(a) showed that the evaporator temperature was higher at the first stable operation, but the flow rate was lower. It showed that there were more bubbles in the CC which deteriorated the supply of the porous wick, a stable state was formed between the LHP and the environment. The gas-liquid phases in the CC were at metastable state. Once the stability was lost balance, such as bubble shrinkage, the

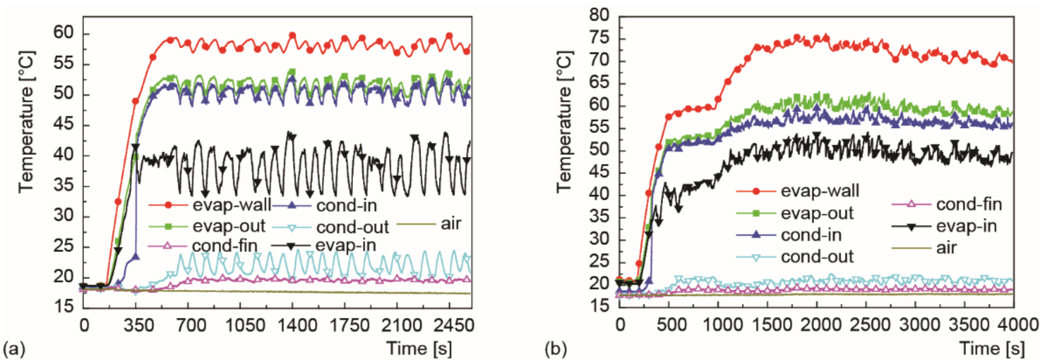

Figure 6. Start-up of the LHP, Q = 48 W, θ = 10°, α = 50 vol.%

liquid supply to porous wick was improved, the flow rate increased, and the LHP formed another stable state. Of course, the stability state was broken and the temperature of the evaporator was likely to increase, as shown in fig. 7(b).

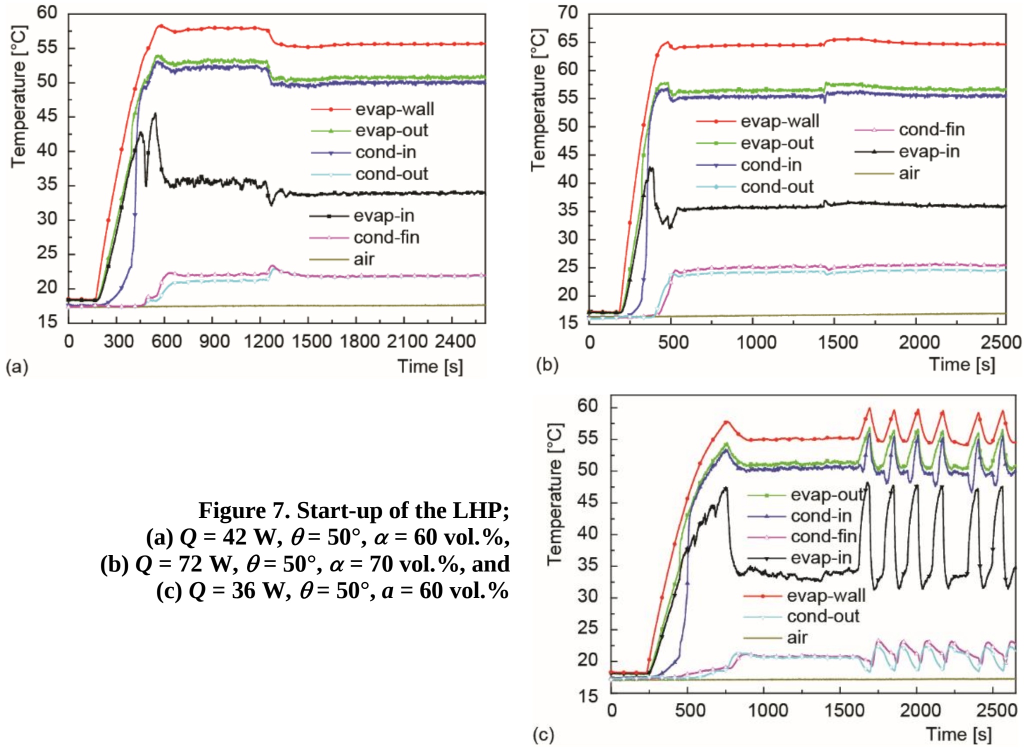

Figure 7. Start-up of the LHP;
(a) Q = 42 W, θ = 50°, α = 60 vol.%,
(b) Q = 72 W, θ = 50°, α = 70 vol.%, and
(c) Q = 36 W, θ = 50°, a = 60 vol.%

The LHP might not form a new stability state when its stability state was broken. As shown in fig. 7(c), the LHP was finally in a temperature oscillation state. The reason was that under the combined action of parasitic heat leakage and reflux liquid, the bubbles in the CC were always in a cycle of increasing and decreasing, and the external appearance was temperature oscillation.

Conclusions

The temperature hysteresis of flat-type LHP with methanol as working fluid was studied experimentally, and the following conclusions can be drawn as follows.

- The temperature hysteresis of the flat-type LHP is related to the increase or decrease of heat load. In the low heat load zone, the temperature of evaporator at Q-step down is higher than that of Q-step up. In the high heat load zone, the temperature of evaporator at Q-step down is lower than that of Q-step up.
- At some heat load, temperature oscillations occur in the LHP, and the temperature oscillation is more violent at Q-step down.
- The temperature hysteresis of LHP is closely relation to the state of the gas-liquid phases in the compensation chamber. The temperature of the evaporator changes with the change of the gas phase in CC.
- The initial temperature affects LHP final operating temperature, especially in the case of little working fluid filling rate.
- The LHP can change from one stability state to another under same heat load. Sometimes it will change from a stability state to a temperature oscillations state.

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Nomenclature

air – ambient air
cond-fin – fin of condenser
cond-in – condenser inlet
cond-out – condenser outlet
evap-in – evaporator inlet
evap-out – evaporator outlet
evap-wall – active zone of evaporator
Q – heat load, [W]
T – temperature, [°C]

Greek symbols

α – working fluid filling rate, [%]
θ – elevation angle, degree [°]

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