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1 **Experimental study on operating characteristics of a dual compensation**
2 **chamber loop heat pipe in periodic acceleration fields**

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13
14 **Abstract:** Systematic experiments were firstly designed and conducted to investigate the
15 operating characteristics of a dual compensation chamber loop heat pipe (DCCLHP) under
16 periodic acceleration conditions. A new acceleration test rig was built to generate acceleration
17 magnitude up to 11 g. The heat load ranged from 150 W to 300 W. Three different periodic
18 acceleration patterns, two loading modes and two acceleration directions were used to study
19 their influence on the operating characteristics of the DCCLHP. The results demonstrated that
20 the loop temperature could periodically oscillate with the periodic change of the acceleration. A
21 large acceleration could lead to a high operating temperature. Configuration B could cause the
22 lower operating temperature than configuration A for a fixed case. There were stable operating
23 temperature difference and thermal resistance variation before and after the periodic
24 acceleration acting for the loading mode 1. Temperature overshooting after unloading the
25 periodic acceleration was also confirmed for the loading mode 2. Such phenomena could be
26 explained by the change of the vapor-liquid distribution in the loop and the heat leak from the
27 evaporator to the compensation chambers (CCs). The loop temperature oscillation with
28 different frequency and amplitude might also occur during each periodic acceleration. For the
29 cases of 150 W and configuration A, the acceleration effect could trigger the operating
30 temperature exceeding 60 °C. Our work proves significant phenomena existing in the DCCLHP
31 and presents detailed analysis, which would be of great importance for the development of new
32 generation of loop heat pipe used in aircraft thermal management system.

33 **Keywords:** Loop heat pipe; Dual compensation chambers; Periodic acceleration force;
34 Operating characteristics.

35 **Nomenclature**

36 R Thermal resistance, K/W
37 Q_e Heat load, W
38 T_{in} Inlet temperature of cold plate, K
39 T_{out} Outlet temperature of cold plate, K
40 \bar{T}_{cp} Average temperature of cold plate, K

41 **Acronyms**

42 CC Compensation chamber
43 DCCLHP Dual compensation chamber loop heat pipe
44 LHP Loop heat pipe
45 RTD Resistance temperature detector

46 **1. Introduction**

47 With the rapid development of aerospace technology, the conventional cooling technology
48 cannot meet the thermal management demand of electronic devices with higher and higher heat
49 dissipation power. New cooling technique has become an urgent demand for solving the
50 cooling problems [1,2]. Loop heat pipe (LHP), an efficient two-phase heat transfer component,
51 has attracted increasing attentions since it was invented [3,4]. It has many advantages including
52 long heat transport distance, strong anti-gravity ability, high heat transfer efficiency and
53 accurate temperature control ability. With such promising properties, LHP has been widely
54 used in the area of aerospace and terrestrial electronics in recent years [5,6].

55 LHP is mainly composed of evaporator, condenser, compensation chamber (CC), liquid and
56 vapor transport line. It transports heat by evaporating and condensing the working fluid from
57 the evaporator and condenser, respectively. Nowadays, a large number of experimental and
58 numerical investigations have been conducted on the steady-state operation and startup
59 performance [7-9], structure design [10,11] and internal visualization [12,13] for the LHP with
60 a single cylindrical CC. Previous researches have brought people with deeper insights of the
61 operating principle and heat transfer mechanism.

62 Compared with the conventional heat pipe, LHP shows its excellence as it overcomes the
63 inherent structural limitations and also retains the merits of the traditional one. High heat
64 transfer ability can be maintained for a long distance in terrestrial gravity due to its special
65 capillary core structure. However, in the thermal tests in gravity, some orientations between
66 evaporator and CCs will occasionally cause the difficulty in supplying the liquid and the LHP
67 even cannot startup. To solve the dilemma, the concept of a dual compensation chamber loop
68 heat pipe (DCCLHP) is proposed. It has two CCs at the both ends of evaporation. Previous
69 studies have investigated the operating characteristics of DCCLHPs. Gluck and Gerhart [14]
70 studied the performance of the DCCLHP using ammonia as working fluid. They found that it
71 could startup and work normally under different configurations between evaporator and CCs.
72 Operation features at nine different orientations were summarized in their study [15]. Long and
73 Ochterbeck [16] experimentally investigated the operating performance of a DCCLHP at
74 transient cyclic heat loads and different orientations, showing that the temperature overshoot
75 before starting up increased with the increase of the tilt angle of the evaporator. The
76 performance at constant heat load was similar to that at cyclic heat load with frequency more
77 than 0.1 Hz. The research group led by Lin [17-20] inspected the operating performance
78 systematically and tried to give insight into the operating mechanism of the
79 ammonia-strain-steel DCCLHP. They also confirmed that the DCCLHP could operate normally
80 at any orientation but show different operating performance at different orientations. Based on
81 the visual observations, they observed the flow inside the DCCLHP and investigated the
82 startup behavior, temperature hysteresis and instability. They believed that the different startup
83 performance derived from the change of the vapor-liquid distribution and the heat leak from
84 the evaporator to the CCs. Chang *et al.* [21, 22] experimentally investigated the startup and
85 operating performance of the DCCLHP anti-icing system. Stainless steel with nickel wick was
86 used. Ethanol and ethanol-water mixture were utilized as working fluid. The results showed
87 that the angle attack could significantly affect the operating temperature and led to a
88 temperature oscillation of the anti-icing system. Moreover, the DCCLHP with 60%
89 concentration of mixture operated more robustly and stably than that with pure ethanol.

90 However, when the aircraft combats or maneuvers, airborne electronic devices suffer from
91 acceleration forces with different directions and magnitudes. Correspondingly, the operating

92 performance of the LHP used to cool the electronic devices will vary. To date there are only a
93 few reports which show the operating performance of the conventional LHP and the DCCLHP
94 subjected to acceleration force. Ku *et al.* [23,24] carried out a series of experiments on a LHP
95 subjected to variable acceleration ranging from 1.2 g to 4.8 g. It was found that the LHP could
96 startup and operate under all working conditions. The temperature oscillation was also
97 observed. Fleming *et al.* [25] studied the operation characteristics of titanium-water based LHP
98 under standard and elevated acceleration fields. In their works, the heat load on evaporator and
99 CC was 100 W-600 W and 0-50 W, respectively. The radial acceleration ranged from 0 to 10 g.
100 The results proved that the dry-out conditions occurred more readily with the heat load
101 between 100 W and 400 W. The radial acceleration had little effect on the thermal resistance
102 and evaporative heat transfer coefficient of the LHP. Yerkes *et al.* [26,27] studied the operating
103 performance of a LHP via experiment under combined steady-periodic acceleration and
104 constant heat load conditions. They found that the periodic acceleration force with greater
105 frequency and peak-to-peak amplitude showed less detrimental impact on the LHP
106 performance. If decreasing frequency and increasing peak-to-peak amplitude, however,
107 detrimental impact on that aggravated. In addition, the transient operating performance of a
108 titanium-water based LHP subjected to a phase-coupled evaporator heat input and acceleration
109 field was studied in detail [28]. It was found that the condenser temperature and phase angle
110 could change the time of LHP operating failure. Xie *et al.* [29,30] carried out experimental
111 studies on the operating behaviors of a stainless steel-ammonia DCCLHP under terrestrial
112 gravity and constant acceleration conditions. The results revealed that the transition of the
113 operation mode was a function of acceleration direction, magnitude and heat load. The
114 DCCLHP could startup and operate normally even the acceleration was up to 11 g.
115 Acceleration effect significantly affects the startup performance at small heat load. Besides,
116 reverse flow, temperature oscillation and evaporation in the evaporator core phenomena were
117 observed.

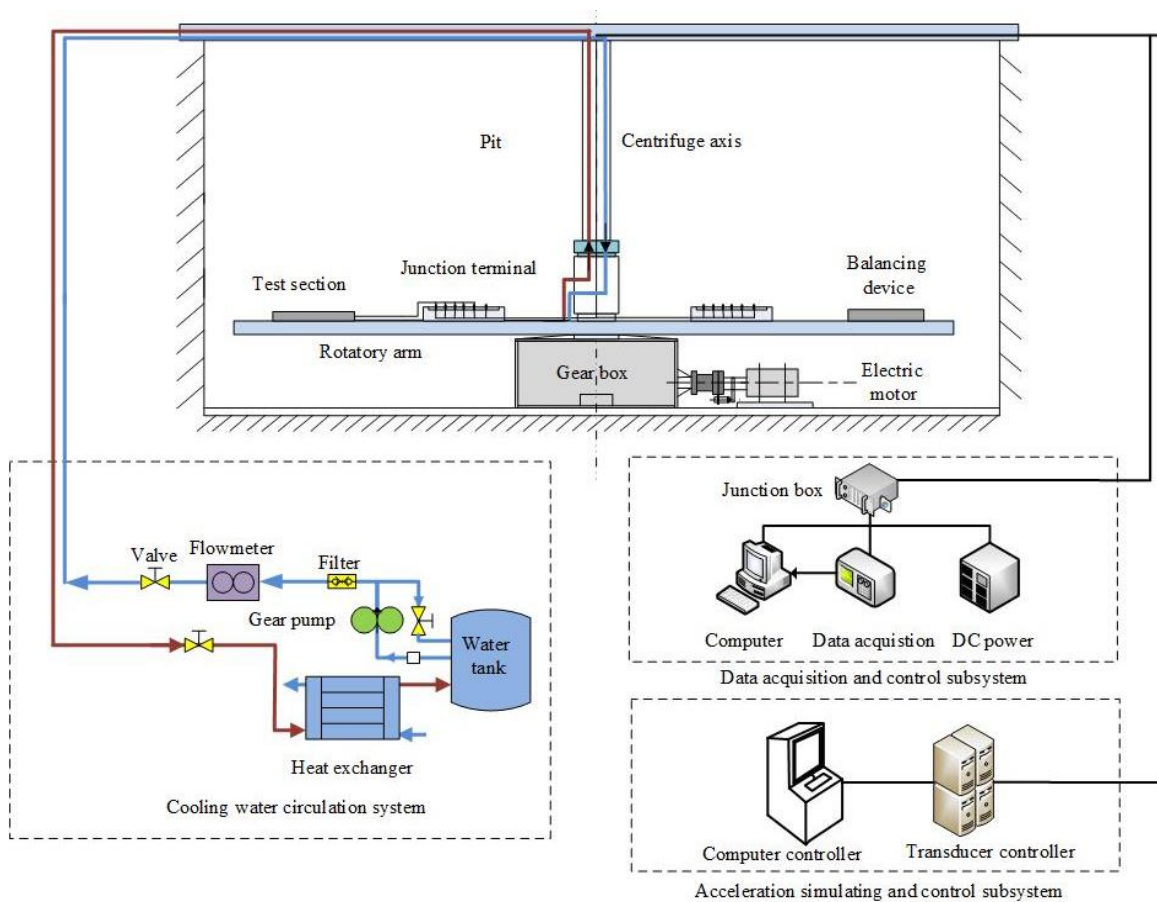
118 To the best of our knowledge, there are no detailed experimental data available in literatures
119 concerning the effect of the varied acceleration force on the DCCLHP, especially the periodic
120 acceleration force. Therefore, our study aims to provide comprehensive experimental data
121 exploring the transient operating performance of a DCCLHP under periodic acceleration

122 conditions. Three different periodic acceleration patterns with different acceleration
123 magnitudes, two loading modes with different heat loads and accelerations as well as two
124 acceleration directions are applied, compared and analyzed in this work.

125 2. Experimental apparatus and test parameters

126 2.1 Experimental apparatus

127 The experiment to investigate the operating performance of the DCCLHP under periodic
128 acceleration force was performed at the Reliability and Environmental Engineering Laboratory
129 at BeiHang University, Beijing, China. Fig. 1 presents the schematic diagram of the
130 experimental test rig which mainly includes cooling water circulation subsystem, data
131 acquisition and control subsystem, acceleration simulating and control subsystem as well as
132 test section.



133
134 Fig.1 The structure of the experimental system.
135 In order to avoid the interaction of each component under acceleration field, only test section
136 including the DCCLHP and a cold plate was arranged on the rotational arm. The other devices
137 were placed on a stationary console. The cooling water circulation subsystem mainly consists

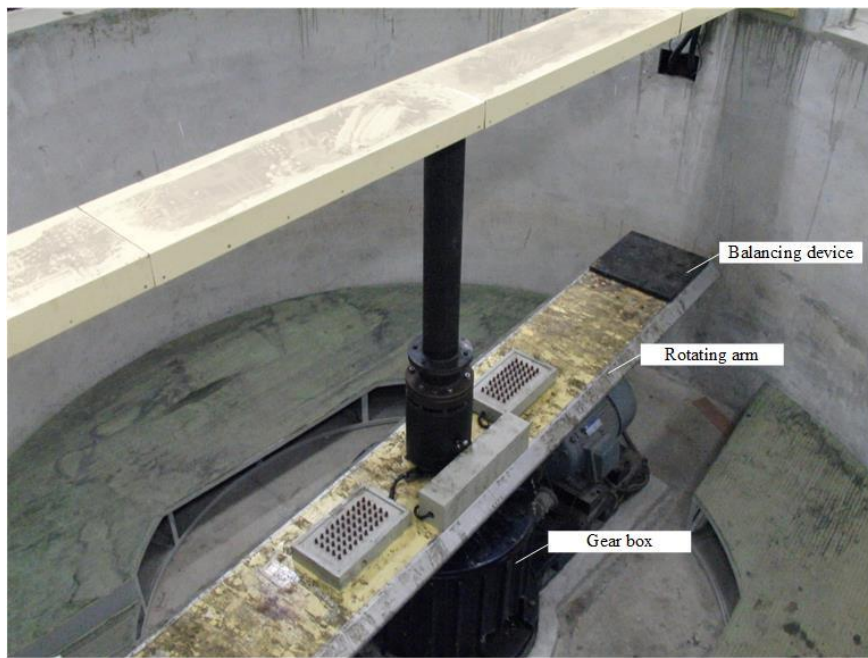
138 of a thermostatic water tank, gear pump, mass flow rate (DMF-1-2), plate heat exchanger and
139 cold plate. The gear pump driven by a variable-frequency driver circulated the cooling water in
140 the loop. The thermostatic water tank provided the cooling water with a constant temperature at
141 19 °C. The accurate flow rate was measured by mass flow meter based on Coriolis force with
142 an accuracy of $\pm 0.5\%$. The heat from the DCCLHP was transferred to the cooling water inside
143 the aluminum cold plate (type 6061). Then the cooling water was cooled to a lower
144 temperature after flowing through the plate heat exchanger. Finally, the cooled water returned
145 back to the thermostatic water tank.

146 In the data acquisition and control subsystem, the DC power supply (DH1716A-13)
147 provided constant voltage and current to the flexible polyimide film electric resistance heater,
148 which was adhesively attached on the outer surface of the evaporator of the DCCLHP. The heat
149 load ranging from 0 to 400 W could be applied to the evaporator by changing the output
150 voltage and current within the range of 0-250 V and 0-5 A, respectively. Resistance
151 temperature detectors (RTDs) Pt100 were used to measure the temperature of the DCCLHP,
152 inlet and outlet temperature of the cold plate, and ambient temperature. These temperatures and
153 mass flow rate were recorded by the Agilent 34970A and saved in a remote computer placed in
154 the control room.

155 The acceleration simulating and control subsystem provided the required acceleration force,
156 which was generated by the rotational arm of the centrifuge spinning clockwise. An electric
157 motor drove the rotational arm to rotate by a gear box. These facilities were installed in a pit
158 and controlled by a remote computer controller and transducer controller. The acceleration
159 magnitude and actuation duration were set by the computer controller. To get the required
160 acceleration magnitude up to 11 g, the test section should be arranged on a set location on the
161 rotational arm. The accuracy of the acceleration is $\pm 5\%$ of the given value. The continuous
162 operation duration of the centrifuge was no more than 1 hour for the issue of safety. The
163 stationary and rotational parts of the water loop tubes, signal wires and electrical wires for
164 heating were linked up by the liquid collecting ring and the electric slip ring, respectively. Both
165 the liquid collecting ring and the electric slip ring installed in the centrifuge axis were specially
166 designed to ensure the flow and electric current working properly as the rotational arm was
167 rotating during the test. Fig. 2 depicts a photo of the centrifuge and the test section horizontally

168 arranged on the rotational arm.

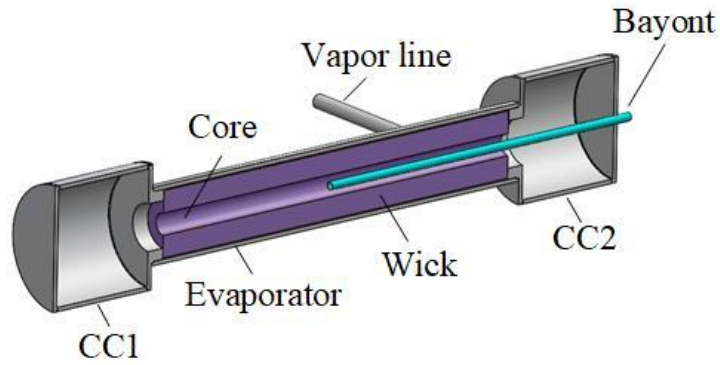
169 In the test section, a stainless steel-ammonia DCCLHP manufactured in the China Academy
170 of Space Technology was horizontally installed in a stainless steel enclosure. The filling
171 quantity of working fluid was insufficient which means that the evaporator core could not be
172 full of liquid under all conditions. Fig. 3 shows a picture of the test object and the internal
173 construction of the evaporator and the CCs. The overall dimension of the DCCLHP is 565 mm
174 × 469 mm × 25 mm. The major design parameters of the test DCCLHP are summarized in
175 Table 1.



176

177 Fig.2 The diagram of the centrifuge.

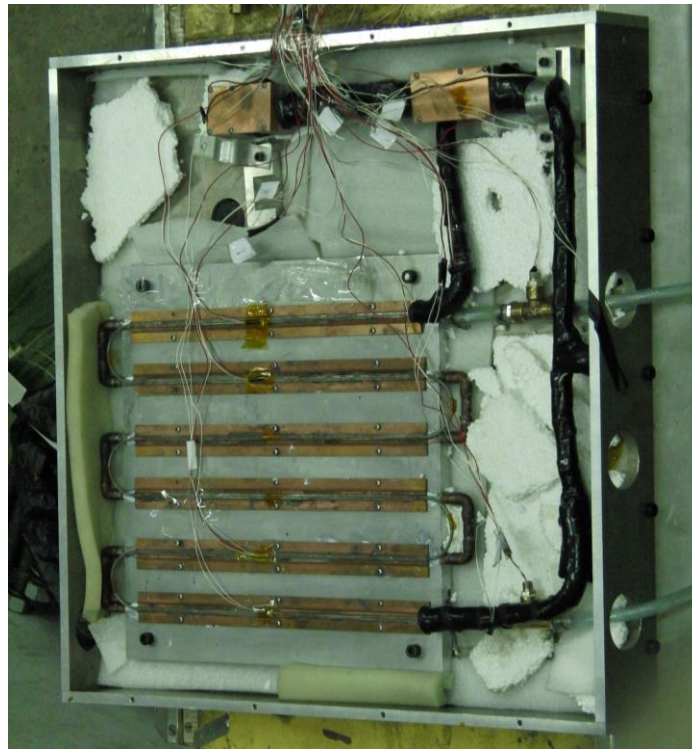
178 As shown in Fig. 3 (a), the bayonet passed through one CC and was extended to the middle
179 point of the evaporator core to discharge the vapor bubbles from the evaporator core at any
180 arrangement orientation. A nickel wick with a pore radius of 1.5 μm was used only in the
181 evaporator. The vapor line, liquid line and condenser line were all smooth round stainless steel
182 tubes with an outer diameter of 3.0 mm. The condenser line was welded to six copper fins
183 which were fixed on the top surface of the cold plate with screws, as shown in Fig. 3 (b).
184 Moreover, the thermal conductive grease was used between the copper fins and the cold plate
185 to decrease the contact thermal resistance. In order to reduce the heat transfer between the
186 DCCLHP and the surroundings, the whole DCCLHP were wrapped with insulation materials
187 and the stainless steel enclosure was crammed with glass wool.



188

189

(a) Internal structure of the evaporator



190

191

(b) A photo of the test DCCLHP

192

Fig.3 A photo of the test DCCLHP and internal structure of the evaporator

193

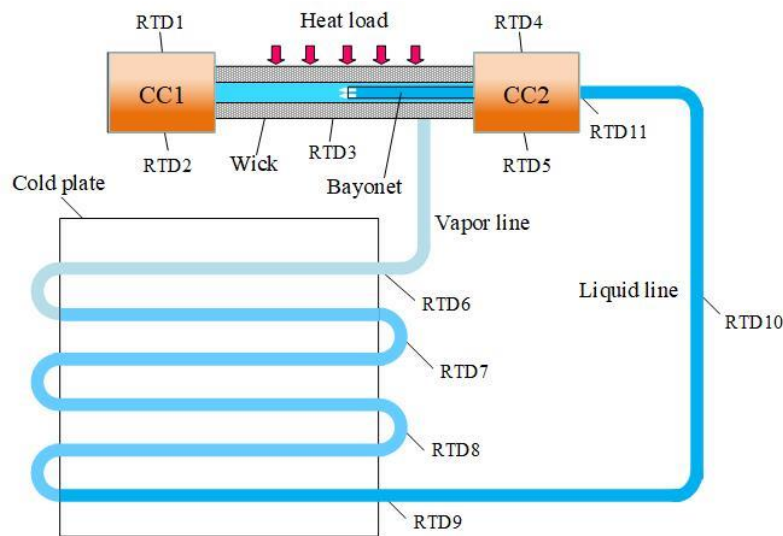
Table 1 Major design parameters of the test DCCLHP.

Evaporator	O.d/i.d. × length of casing	20 mm/18 mm×209 mm
	Material	Stainless steel
Wick	Pore radius	1.5 μm
	Porosity	55%
	Permeability	$>5 \times 10^{-14} \text{ m}^2$
	O.d/i.d. × length	18 mm/6 mm×190mm
Vapor line	Material	Nickel
	O.d/i.d. × length	3 mm/2.6 mm×225 mm
Liquid line	Material	Stainless steel
	O.d/i.d. × length	3 mm/2.6 mm×650 mm
	Material	Stainless steel

Condenser line	O.d/i.d. × length	3 mm/2.6 mm×2200 mm
	Material	Stainless steel
CCs	O.d/i.d. × length	27 mm/25 mm×64 mm
	Material	Stainless steel
Working fluid	Ammonia	

194 When the test section was fixed on the end of the rotational arm, non-uniform radial
195 acceleration forces on the DCCLHP were generated at different radius positions. GB/T2423.15
196 requires that the acceleration magnitude should range from 90% to 130% related to the value at
197 a certain rotational radius over the DCCLHP. Thus, the DCCLHP should be installed at
198 approximate 1.9 m of rotational radius of the centrifuge. Correspondingly, the value of the
199 rotational radius should also be set to 1.9 m in the acceleration control software.

200 In the current study, fourteen RTDs were utilized to monitor the temperature in the test. Fig.
201 4 shows the RTD locations of the measuring points along the DCCLHP. RTD1 and RTD2,
202 RTD4 and RTD5 were attached to the top and bottom of the outer surface of CC1 and CC2,
203 respectively. RTD3 was located at the middle position on the evaporator. RTD6 was located at
204 the end of the vapor line, and that is at the inlet of the condenser. RTD7 and RTD8 were
205 located on the condenser line, respectively. RTD9, RTD10 and RTD11 were located at the inlet,
206 middle and outlet position of the liquid line, respectively. RTD12 and RTD13 were used to
207 measure the cooling water temperatures at the inlet and outlet of the cold plate, respectively.
208 RTD14 was used to monitor the ambient temperature.



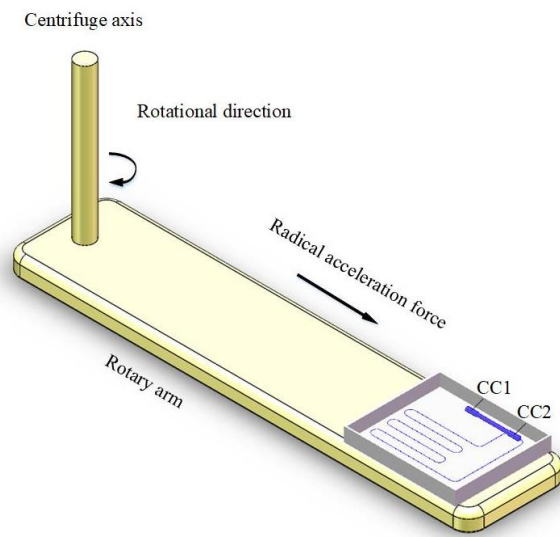
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Fig.4 Schematic diagram of RTDs locations on the DCCLHP.

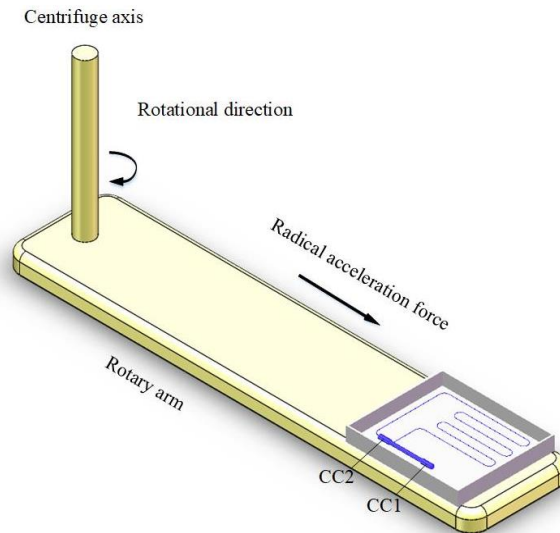
211 2.2 Test parameters

212 In the current work, tests were conducted with the following two different configurations,
213 namely configuration A and B as shown in Fig. 5. For both configurations, the DCCLHP was
214 placed on a horizontal plane and the longitudinal axis of the evaporator and CCs was aligned
215 with the direction of the radial acceleration. The main difference for both configurations was
216 that the radial acceleration direction pointed from CC1 to CC2 for configuration A while it
217 pointed from CC2 to CC1 for configuration B.



218
219

(a) Configuration A



220
221

(b) Configuration B.

Fig.5 Two different acceleration directions.

222
223 Two loading modes, *i.e.*, loading mode 1 and loading mode 2, were used to apply the heat
224 load and acceleration force on the DCCLHP. For loading mode 1, the heat load was applied on

225 the evaporator firstly and then the acceleration force was applied until the DCCLHP reaching a
 226 steady state. For loading mode 2, the heat load and the acceleration force were acted on the
 227 DCCLHP simultaneously. The heat load ranged from 150 W to 300 W and the acceleration
 228 magnitude from 0 g to 11 g. Moreover, three different periodic acceleration force were
 229 generated and used to study the effect on the operating performance of the DCCLHP. Fig. 6
 230 presents these periodic acceleration patterns in the tests. In each periodic acceleration pattern,
 231 the action time of the acceleration force was 5 minutes. In periodic acceleration pattern 1, 0 g
 232 referred to no acceleration action but only the gravity and the lasting time was 1 minute. In
 233 order to compare different cases, the cooling water temperature at the inlet of the cold plate
 234 was kept at 20.3 ± 0.5 °C. The indoor temperature was kept at about 26 °C.



235

236

Fig.6 Three different periodic acceleration patterns.

237 *2.3 Test procedure*

238 Calibrations of the RTDs and mass flow meter were conducted prior to the formal test. The
 239 validation of the experimental setup was verified by measuring the thermal conductivity of a

240 pure copper bar with the diameter of 30 mm under terrestrial gravity conditions. Detailed
241 descriptions are available in Ref. [30].

242 Before each test, the test section was arranged at a proper location on the rotational arm for
243 the given acceleration direction. When starting the formal tests, the data acquisition and control
244 subsystem was firstly operated and then the cooling water circulation subsystem was turned on.
245 The cooling water circulated until the system reaching a steady state. Consequently, for the
246 loading mode 1, the DCCLHP first operated to a steady state at a given heat load on the
247 evaporator and then the acceleration simulating and control subsystem started to apply the
248 acceleration force. While for the loading mode 2, the film heater and the centrifuge were turned
249 on simultaneously. Then the effect of different magnitudes and directions of the periodic
250 acceleration force, and that of different heat loads on transient operating performance was
251 investigated.

252 **3. Results and discussion**

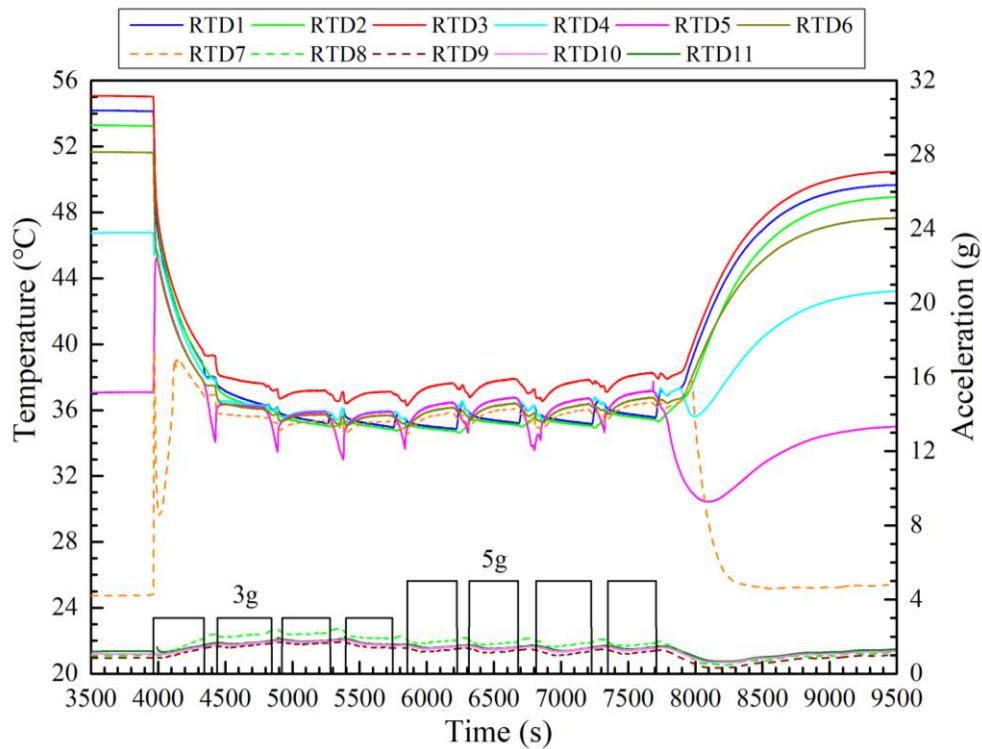
253 The operating performances of the DCCLHP subjected to various periodic acceleration
254 patterns and loading modes are presented in the following sections, including several particular
255 phenomena such as stable operating temperature difference, temperature overshooting after
256 unloading, temperature oscillation and excessive operating temperature.

257 *3.1 Operating performance during periodic acceleration*

258 In order to analyze the operating performance of the DCCLHP under different periodic
259 acceleration conditions, Fig. 7 depicts the loop temperature profiles at 150 W and loading
260 mode 1 under configuration B and the periodic acceleration pattern 1, 2 and 3, respectively.
261 Such results revealed that the loop temperature under periodic acceleration conditions was
262 obviously lower than that without periodic acceleration force acting. The loop temperature
263 showed periodic oscillation with the acceleration periodic change. Moreover, the temperature
264 oscillation at the acceleration pattern 1 was more than that at the acceleration pattern 2 and 3.
265 The higher the acceleration magnitude, the higher the operating temperature.

266 As shown in Fig. 7 (a), the loop temperature showed a periodic fluctuation under the
267 periodic acceleration force conditions. Before applying the first 3 g of the acceleration force,
268 the evaporation temperature indicated by RTD3 was 55.1 °C. The upper and lower surface

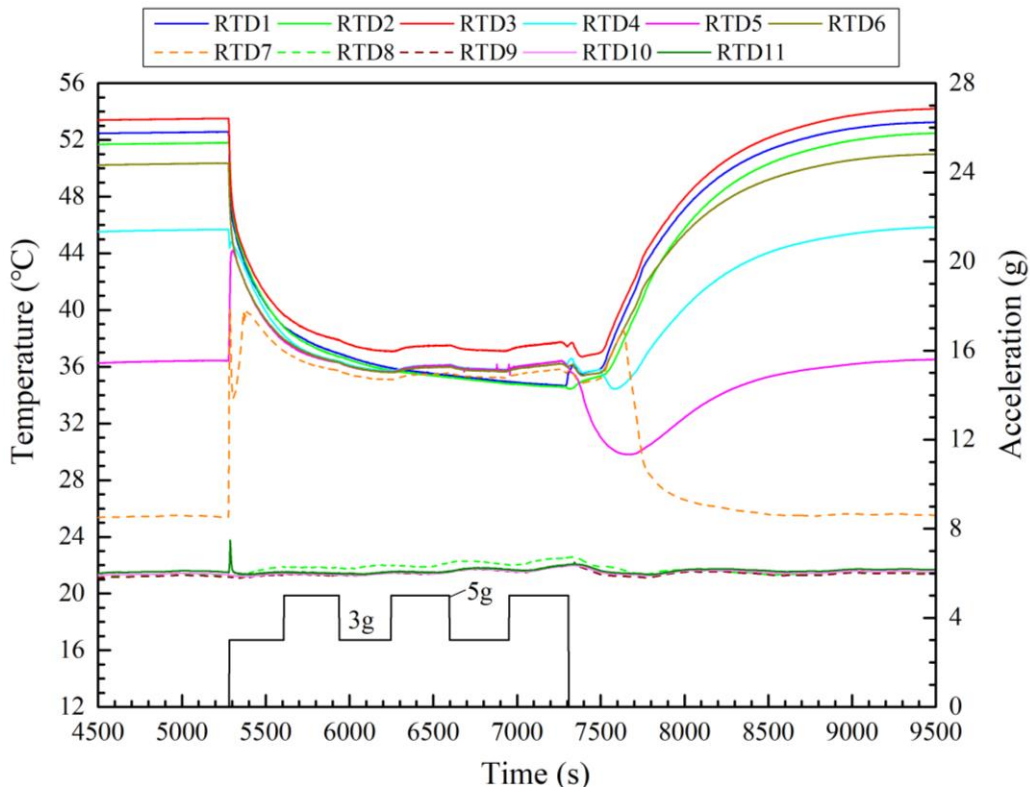
269 temperature of the CC1 and CC2 was 54.2 °C, 53.3 °C, 46.8 °C and 37.1 °C, respectively. The
 270 temperature of RTD1 to RTD4 dropped rapidly while the RTD5 temperature increased instantly
 271 and then decreased quickly upon applying the periodic acceleration force. The main reason for
 272 this was that the vapor-liquid distribution in the loop was changed by the acceleration force,
 273 which directed from the CC2 to CC1 under configuration B. It enabled more liquids with lower
 274 temperature to enter the CC1 but more vapor with higher temperature to enter the CC2.
 275 Consequently, the CC1 temperature decreased while the RTD5 temperature rose rapidly.
 276 Moreover, the significant increase of the RTD7 temperature and the slight increase of both
 277 RTD8 and RTD9 indicated that the vapor-liquid interface moved forward to somewhere
 278 between RTD7 and RTD8 from that between RTD6 and RTD7. The acceleration effect
 279 enlarged the area of two-phase region in the condenser. According to the temperature variation
 280 of RTD7, RTD8 and RTD9, it could be further inferred that the vapor-liquid interface located
 281 closer to the RTD7 point. Thus, the external loop pressure drop caused by acceleration could be
 282 neglected. Because the vapor-liquid distribution in the CCs contributed to decreasing the heat
 283 leak from the evaporator to the CCs, and thereby the temperature of the evaporator and the CCs
 284 dropped continuously.



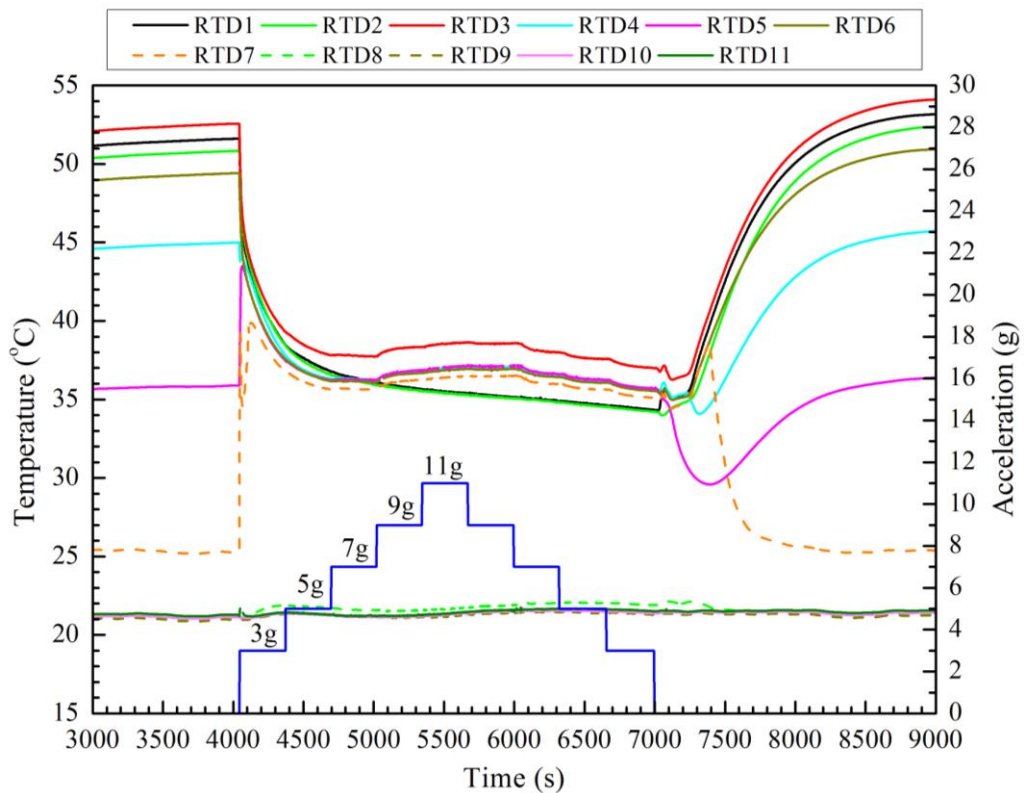
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286

(a) Temperature profiles at acceleration pattern 1



(b) Temperature profiles at acceleration pattern 2



(c) Temperature profiles at acceleration pattern 3

Fig.7 Temperature curves at 150 W, loading mode 1 under configuration B and acceleration pattern 1, 2 and 3.

After unloading the first 3 g, the temperature of RTD1 to RTD4 rose but RTD5 dropped

294 obviously. The reason could be that the vapor-liquid distribution in the loop was quickly altered
295 to the previous state as the acceleration was removed. Hence the heat leak from the evaporator
296 to the CCs increased. Due to the slight change of RTD11 temperature, the subcooling of the
297 returning liquid kept almost constant. Thus, both CCs temperature rose and the evaporator
298 temperature increased accordingly.

299 When the second 3 g acceleration functioned, the vapor-liquid distribution changed again
300 which would be similar to that in the first 3 g process. The temperature of RTD1 to RTD4
301 dropped and then kept constant while the RTD5 temperature rose to a constant. Moreover, the
302 loop temperature decreased again as the second 3 g was removed. Similarly, the temperature of
303 the evaporator and the CCs during the period from the third 3 g to the fourth 3 g showed the
304 similar variation as the second 3 g. The evaporator temperature varied from 36.4 °C to 37.2 °C.
305 When 5 g was applied, it could be found that the operating temperature was nearly 0.6 °C
306 higher than that under 3 g at a steady state. The temperature of RTD4 to RTD7 showed similar
307 profiles. This indicated that larger acceleration could result in a higher operating temperature
308 and temperature variation.

309 After the periodic acceleration was unloaded at about 7674 s, the whole loop operated in
310 terrestrial gravity. The vapor-liquid distribution in the loop recovered back to the initial state
311 before the acceleration was applied. The temperature of the evaporator and the CCs started to
312 increase after a slight fluctuation. Finally, the whole loop reached a steady state. The final
313 operating temperature was 50.5 °C, which was 4.6 °C lower than the initiate temperature.

314 In Fig. 7 (b), as the first 3 g was applied, the evaporator and the CC1 temperature decreased
315 rapidly, while the upper surface temperature of the CC2 increased firstly and then descended.
316 The RTD7 temperature increased significantly. Meanwhile the RTD8 and RTD9 temperature
317 only changed slightly. It indicated that the vapor-liquid interface was supposed to locate
318 somewhere between RTD7 and RTD8. The acceleration effect altered the vapor-liquid
319 distribution in the loop and further caused the heat leak from the evaporator to the CCs change.
320 Consequently, the loop temperature varied dramatically. During the period of the first 5 g and
321 the second 3 g, the loop temperature dropped continuously except for the RTD8, RTD9 and
322 RTD11 temperature. However, during the period of the second 5 g and the third 3 g and 5 g, the
323 temperature of the evaporator, the CC2 and the liquid line showed a slight increase or decrease

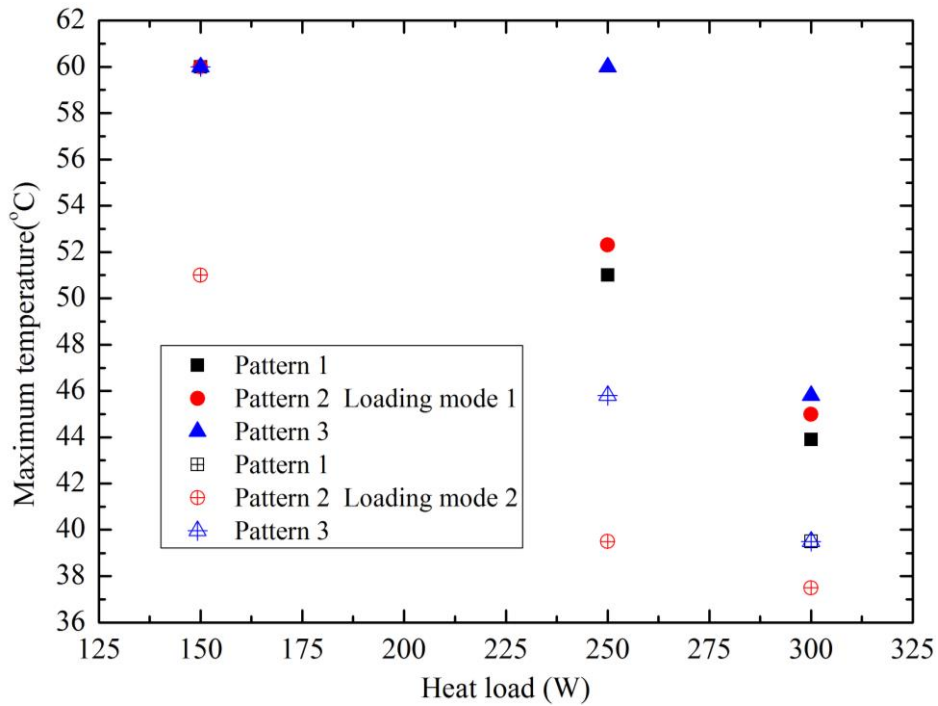
324 as the acceleration increased or decreased. The evaporator temperature changed between 37.0
325 °C and 37.9 °C. After unloading the acceleration force, the temperature of the evaporator and
326 the CCs increased and finally stayed constant.

327 In Fig. 7 (c), the loop temperature change presented a similar trend to that shown in Fig. 7 (a)
328 and (b). Especially when the first 3 g and 5 g were applied, all the loop temperature was almost
329 the same with that shown in Fig. 7 (c). When the acceleration magnitude increased to 7 g, the
330 evaporator temperature decreased to about 37.8 °C. However, the evaporator temperature
331 increased continuously up to about 38.6 °C as the acceleration magnitude further increased to 9
332 g and 11 g. Consequently, the temperature of RTD4 to RTD7 also increased slightly. When the
333 acceleration magnitude decreasing from 11 g to 3 g, the evaporator temperature dropped
334 gradually to about 36.8 °C. During the whole period of the periodic acceleration, the CC2
335 temperature dropped continuously and the RTD8 to RTD11 temperature kept almost constant.
336 After unloading the acceleration force, the loop temperature presented the similar trend to that
337 shown in Fig. 7 (b). Finally, the temperature of the evaporator and the CCs increased to
338 constant.

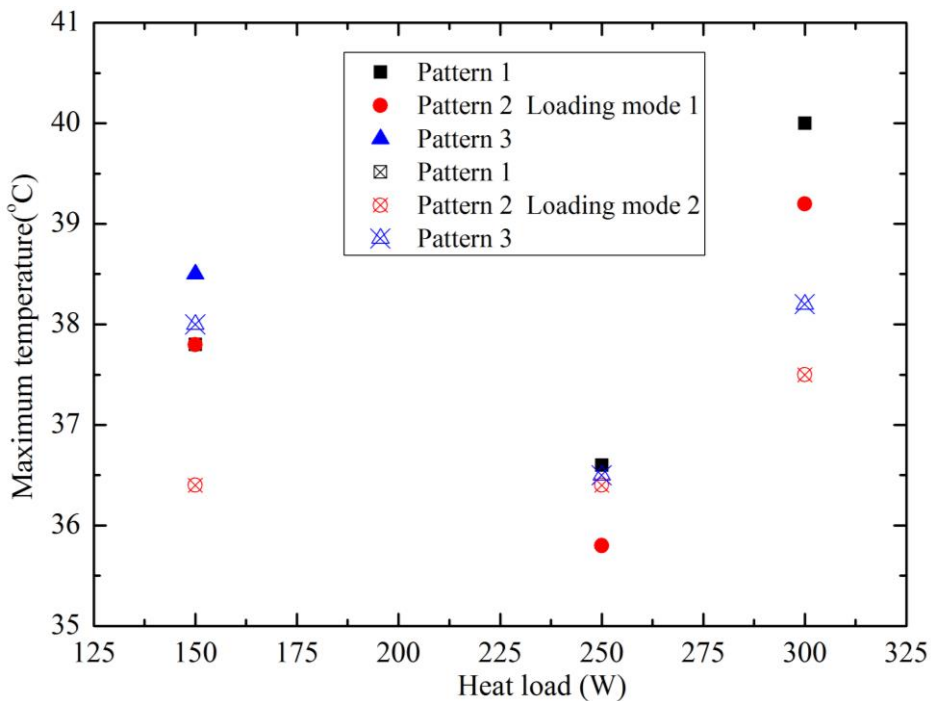
339 In addition, it is worth noting that the operating temperature at 150 W, 200 W and 250 W
340 was lower than that before applying the acceleration force for the cases at the loading mode 1
341 and configuration B. The operating temperature increased periodically with the periodic
342 acceleration force at almost all cases under configuration A. Some cases showed an excessive
343 operating temperature, which would be discussed in the section 3.5.

344 Fig. 8 presents the maximum operating temperature of the DCCLHP during the periodic
345 acceleration with the heat load under configurations A and B respectively. Here, the maximum
346 value of the operating temperature was used during the periodic acceleration except for the
347 initiate stage. For the cases at 150 W/loading mode 1, 250 W/acceleration pattern 3/loading
348 mode 1, as well as 150 W/acceleration pattern 3/loading mode 2, the maximum operating
349 temperature of the DCCLHP under configuration A exceeded the maximum allowable
350 temperature of 60 °C. It can be found from Fig. 8 that the maximum operating temperature
351 decreased with the increase of heat load under configuration A for both loading modes. But it
352 firstly decreased and then increased with the heat load under configuration B. For three
353 acceleration patterns, the maximum operating temperature at loading mode 1 was generally

354 greater than that at loading mode 2 under both configurations A and B.



(a) Under configuration A



(b) Under configuration B

357 Fig. 8 Maximum operating temperature during periodic acceleration with heat load under
 358 configurations A and B
 359
 360

361 In Fig. 8 (a), with the heat load of 150 W and loading mode 1, the maximum operating
 362 temperature exceeded 60 °C for three acceleration patterns. For the heat load of 250 W and 300
 363 W, the maximum operating temperature at acceleration pattern 3 was generally higher than that

364 at acceleration pattern 2, which was higher than that at the acceleration pattern 1. For the cases
365 of loading mode 1 at 300 W, the maximum operating temperature at the acceleration pattern 1,
366 2 and 3 was 43.9 °C, 45 °C and 45.8 °C, respectively. For the cases of loading mode 2 at 300 W,
367 in contrast, it was 39.5 °C, 37.5 °C and 39.5 °C, respectively.

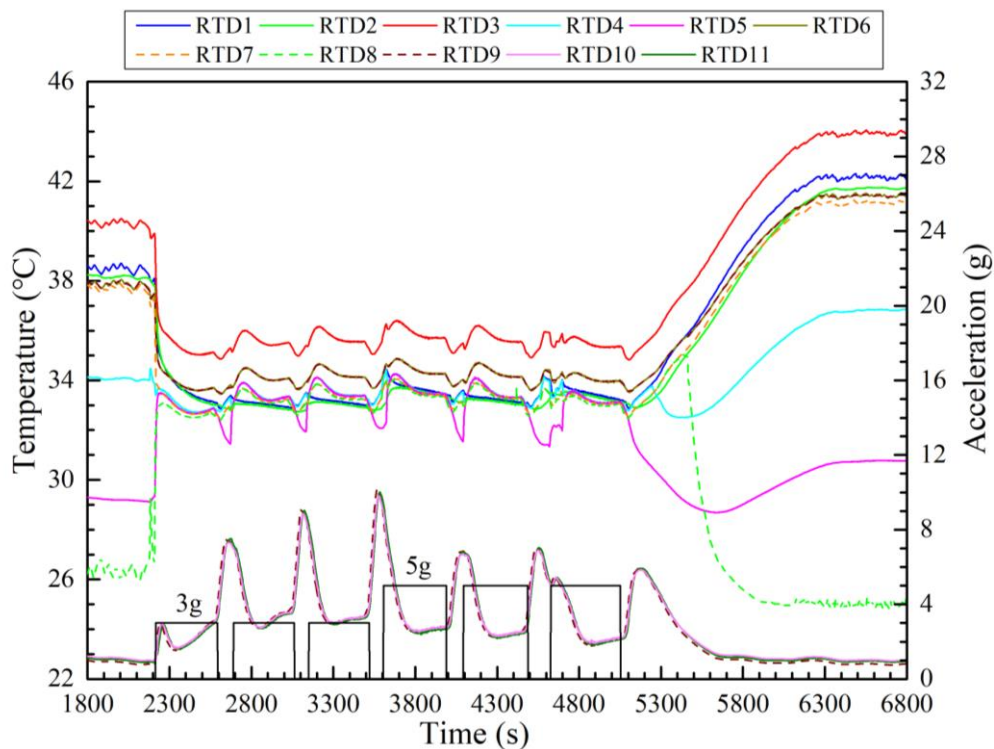
368 Compared to the cases shown in Fig. 8 (a), the maximum operating temperature under
369 configuration B shown in Fig. 8 (b) was significantly lower than that under configuration A.
370 The maximum temperature at the loading mode 1 and 2 for different heat loads was less than
371 40 °C and 38.5 °C respectively. For the cases of 250 W and 300 W, the maximum operating
372 temperature at the acceleration pattern 1 was higher than that at the acceleration pattern 2 as the
373 loading mode 1 was used, which showed an opposite trend with those under configuration A.
374 However, for the loading mode 2, the maximum operating temperature at the acceleration
375 pattern 3 was higher than that at the acceleration pattern 2. It presented the same change to that
376 under configuration A. The maximum operating temperature at the acceleration pattern 1 and 2
377 under 250 W and loading mode 1 was 36.6 °C and 35.8 °C, respectively. The maximum
378 operating temperature at the acceleration pattern 2 and 3 was 36.4 °C and 36.5 °C for the
379 loading mode 2 at 250 W respectively.

380 The study on the effect of the loading mode revealed that the maximum operating
381 temperature at 150 W and the loading mode 1 exceeded 60 °C for all the three acceleration
382 patterns. The DCCLHP showed high operating temperature beyond 50 °C for the cases of 250
383 W and the loading mode 1. For different heat loads, the maximum operating temperature at the
384 loading mode 1 was higher than that at the loading mode 2 in general when the acceleration
385 pattern 1 was applied. For the given heat load, loading mode and acceleration pattern, the
386 maximum operating temperature under configuration A was greater than that
387 under configuration B. The maximum temperature under configuration B was less than 40 °C.
388 Moreover, under configuration A, the maximum operating temperature of the acceleration
389 pattern 3 was the highest, followed by the acceleration pattern 2 and the smallest of the
390 acceleration pattern 1. Under configuration B, the maximum operating temperature of the
391 acceleration pattern 1 at the loading mode 1 was more than that of the acceleration pattern 2.
392 For the cases of the loading mode 2, the maximum operating temperature of the acceleration
393 pattern 3 was greater than that of the acceleration pattern 2.

394 3.2 Stable operating temperature difference

395 For some cases as the loading mode 1 was used, the steady operating temperature of the
396 DCCLHP before applying acceleration force was different from that after unloading
397 acceleration force, although all the conditions like the heat load, the heat sink temperature and
398 the ambient temperature were identical. As shown in Fig. 7, the steady operating temperature
399 difference before and after the periodic acceleration force was 4.6 °C, -0.7 °C and -1.6 °C for
400 the acceleration pattern 1, 2 and 3, respectively.

401 Fig. 9 shows the loop temperature profiles at 250 W, periodic acceleration pattern 2 and
402 loading mode 1 under configuration B. It could be clearly seen from Fig. 9 that the operating
403 temperature of the DCCLHP under acceleration conditions was lower than that in gravity. The
404 operating temperature after removing acceleration force was higher than that before applying
405 acceleration force and showed a slight oscillation. The loop temperatures showed periodic
406 oscillation along with the periodic acceleration force. Especially for the temperature of the
407 liquid line, it oscillated more significantly than that shown in Fig. 7 (a).



408
409 Fig. 9 Temperature profiles at 250 W, acceleration pattern 1 and loading mode 1 under
410 configuration B.

411 Compared to the case shown in Fig. 7, the temperature changes of the evaporator and the
412 CCs were similar after applying the periodic acceleration. But the temperature amplitude of the

413 evaporator and CCs was larger for the case given in Fig. 9. Furthermore, the vapor-liquid
 414 interface moved forward to somewhere between RTD8 and RTD9. A large temperature
 415 oscillation of RTD9 to RTD11 indicated that the subcooling of the returning liquid varied
 416 acutely. During almost all the periods between two periodic accelerations, the temperature of
 417 RTD9, RTD10 and RTD11 increased rapidly. As a result, the evaporator temperature increased
 418 and the vapor-liquid interface moved forward. But the subcooling of the returning liquid
 419 decreased. On the contrary, if the periodic acceleration (3 g or 5 g) existed, the vapor-liquid
 420 interface would move backwards, which induced an increase of the subcooling of the returning
 421 liquid. Additionally, the peak value of the RTD11 temperature corresponded to the valley value
 422 of the upper surface of the CC2. And at these moments, the acceleration was just applied. It
 423 was at about 6400 s that the whole loop reached a quasi-stable state again. The operating
 424 temperature was about 43.9 °C. It showed an increase of 3.5 °C relative to 40.4 °C before the
 425 periodic acceleration.

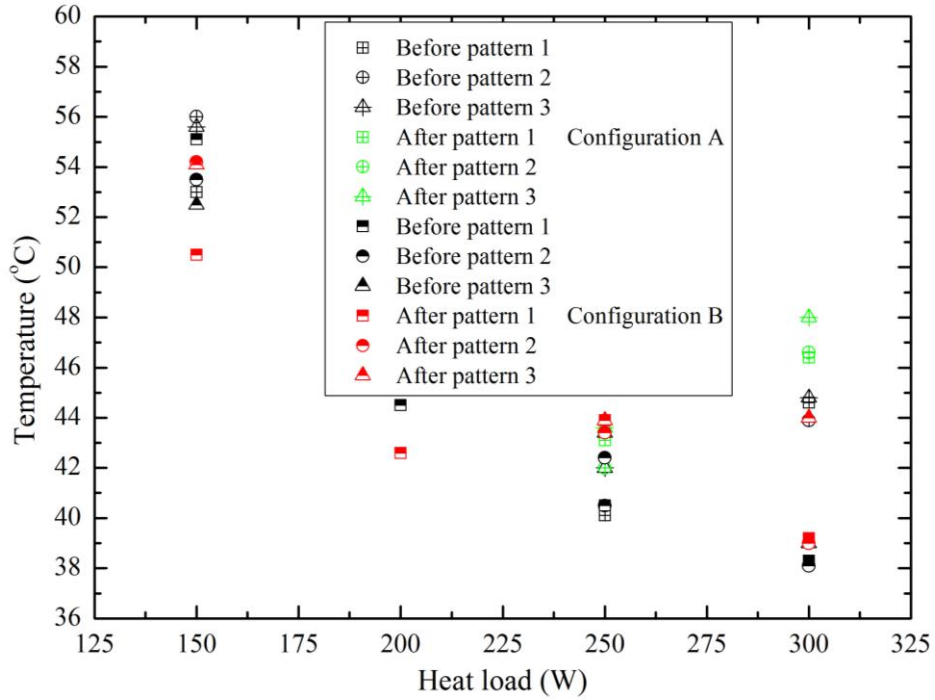
426 Fig. 10 shows the operating temperature and thermal resistance of the DCCLHP before and
 427 after the periodic acceleration patterns under both configurations and loading mode 1
 428 conditions. Here, the thermal resistance of the DCCLHP was determined by the evaporator
 429 temperature and the average temperature of the cold plate.

$$430 \quad R = \frac{T_e - \bar{T}_{cp}}{Q_e} \quad (1)$$

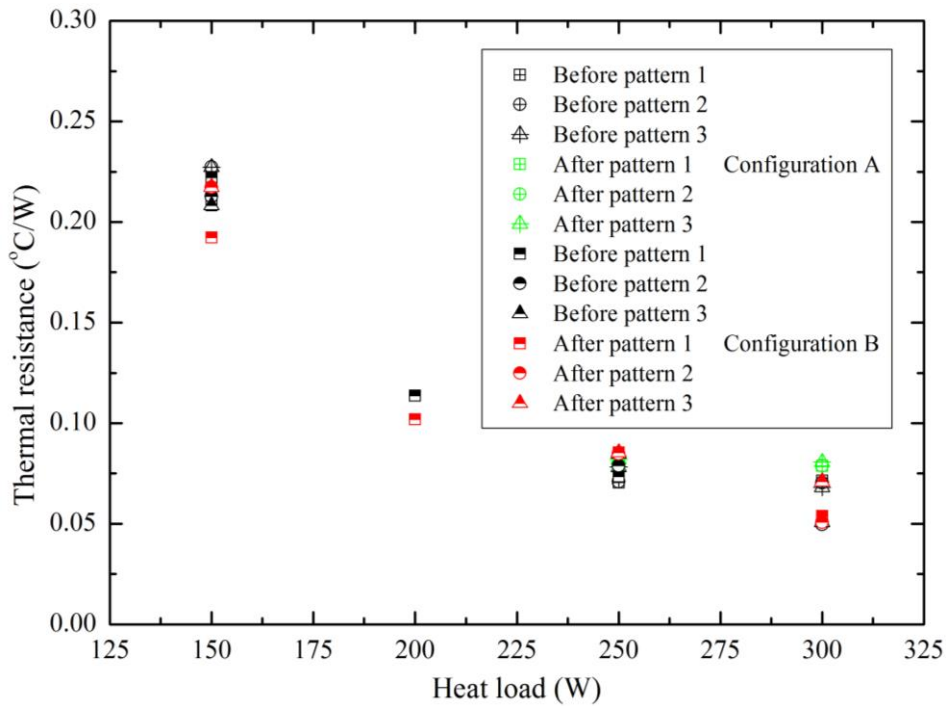
431 where $\bar{T}_{cp} = 0.5(T_{out} + T_{in})$ is the average cold plate temperature, and T_{in} and T_{out} are the
 432 temperature at the inlet and outlet of the cold plate, respectively. Q_e is the heat load on the
 433 evaporator.

434 Fig. 10 indicates an obvious difference in the operating temperature and thermal resistance
 435 for the cases of various heat loads and configurations. In Fig. 10 (a), the operating temperature
 436 after removing the periodic acceleration under configuration B could be higher or lower than
 437 that before applying the periodic acceleration although the operating conditions were the same.
 438 Apparently, the same operating temperature could also occur. It should be random that there
 439 was a stable operating temperature difference. Possible reasons could be attributed to that the
 440 history of the periodic acceleration force acting could change the vapor-liquid distribution and
 441 the heat leak from the evaporator to the CCs. Furthermore, the stable operating temperature

442 increased under the most working cases, especially at 250 W and 300 W after removing the
 443 acceleration patterns. It should be noted that the operating temperature at 150 W under
 444 configuration A exceeded the allowable value after removing the acceleration patterns.
 445 Therefore, the corresponding data did not be displayed in Fig. 10 (a).



(a) Operating temperature



(b) Thermal resistance

448
 449
 450 Fig. 10 Stable operating temperature and thermal resistance vs heat load under all acceleration
 451 patterns and configurations at loading mode 1.

452 As can be seen from Fig. 10 (b), the thermal resistance value decreased with the increase of
453 the heat load for each acceleration pattern and configuration. The maximum value of the
454 thermal resistance was 0.23 °C/W at 150 W and configuration A before applying periodic
455 acceleration pattern 2. The minimum value was 0.05 °C/W at 300 W and configuration B
456 before applying periodic acceleration pattern 2. The thermal resistance value after removing
457 the acceleration patterns was higher than that before applying the acceleration patterns for the
458 most working cases.

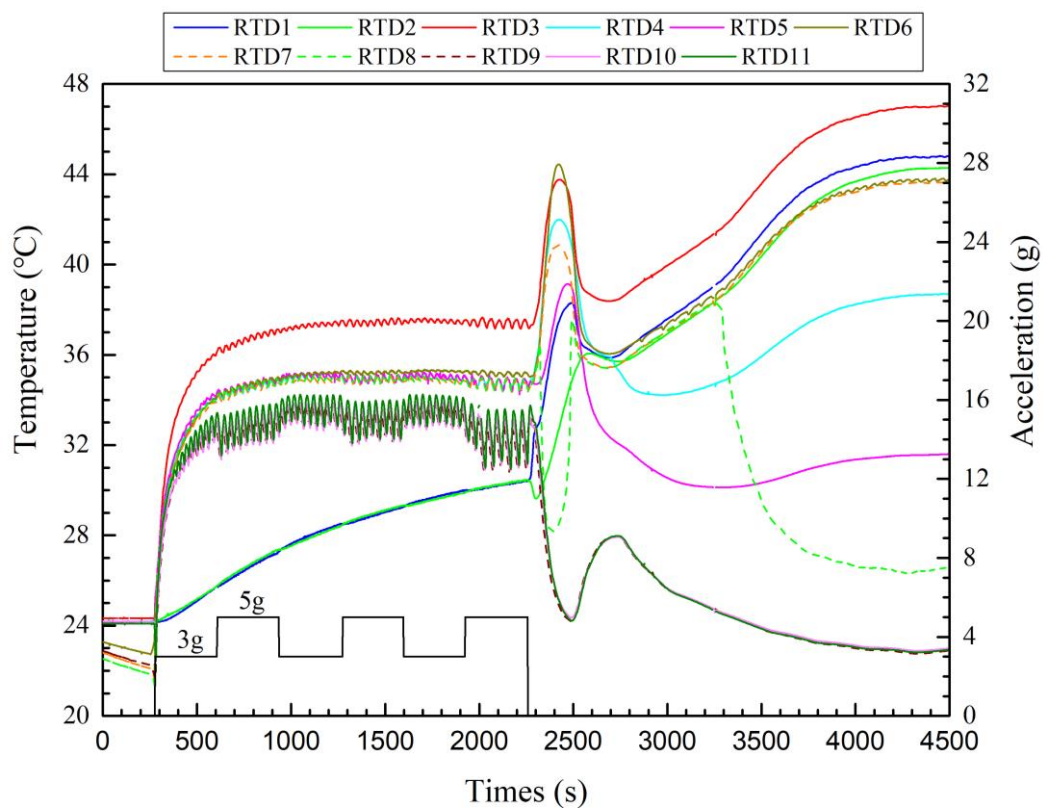
459 *3.3 Temperature overshooting after unloading*

460 For the cases at loading mode 2 with large heat load, the operating temperature of the
461 DCCLHP could significantly overshoot after the periodic acceleration force was removed. Fig.
462 11 presents the temperature evolutions at 300 W, periodic acceleration pattern 2 and loading
463 mode 2 under configuration B. The heat load and the acceleration were applied simultaneously
464 at about 278 s. The DCCLHP started up immediately. The acceleration force resulted in the
465 change of the vapor-liquid distribution in the loop. As more liquid entered into the CC1, the
466 heat leak from the evaporator to the CC1 decreased and the RTD1 and RTD2 temperature rose
467 slowly. After the loop started up, the temperature oscillation of the partial loop occurred except
468 for RTD1 and RTD2 points. The evaporator temperature amplitude was the smallest while the
469 amplitude of the liquid line was the largest during the periodic acceleration force acting. The
470 evaporator temperature was approximate 37.3 °C. Furthermore, the higher the acceleration
471 magnitude, the larger the temperature amplitude of each point.

472 As the acceleration was removed at 2260 s, there was an obvious peak on the temperature
473 curves of the evaporator, vapor line and CC2, while there was an apparent valley value on the
474 temperature curves of the liquid line and CC1. The peak value of the operating temperature
475 reached 43.7 °C. After the peak, the temperature of the evaporator, CC2 and vapor line
476 continuously increased. Finally, the loop achieved a steady state. The final operating
477 temperature was about 46.9 °C. At this time, the vapor-liquid interface in the condenser located
478 somewhere between RTD7 and RTD8.

479 The similar phenomenon was shown in Fig. 12 for the case of 300 W, periodic acceleration
480 pattern 3 and loading mode 2 under configuration B. The acceleration effect caused the

481 variation of the vapor-liquid distribution at the first 3 g just like that shown in Fig. 11.
 482 Temperature oscillations of the evaporator, CC2, vapor line and condenser occurred except for
 483 the CC1. The amplitudes of the evaporator and liquid line temperature were still the smallest
 484 and largest, respectively. Moreover, the temperature amplitude of both components showed a
 485 stepped increase along with the stepped increase of the acceleration magnitude and reached the
 486 maximum values at 11 g. Subsequently, the temperature amplitude showed a stepped drop with
 487 the stepped decrease of the acceleration magnitude. The operating temperature was about 38 °C
 488 under periodic acceleration conditions.

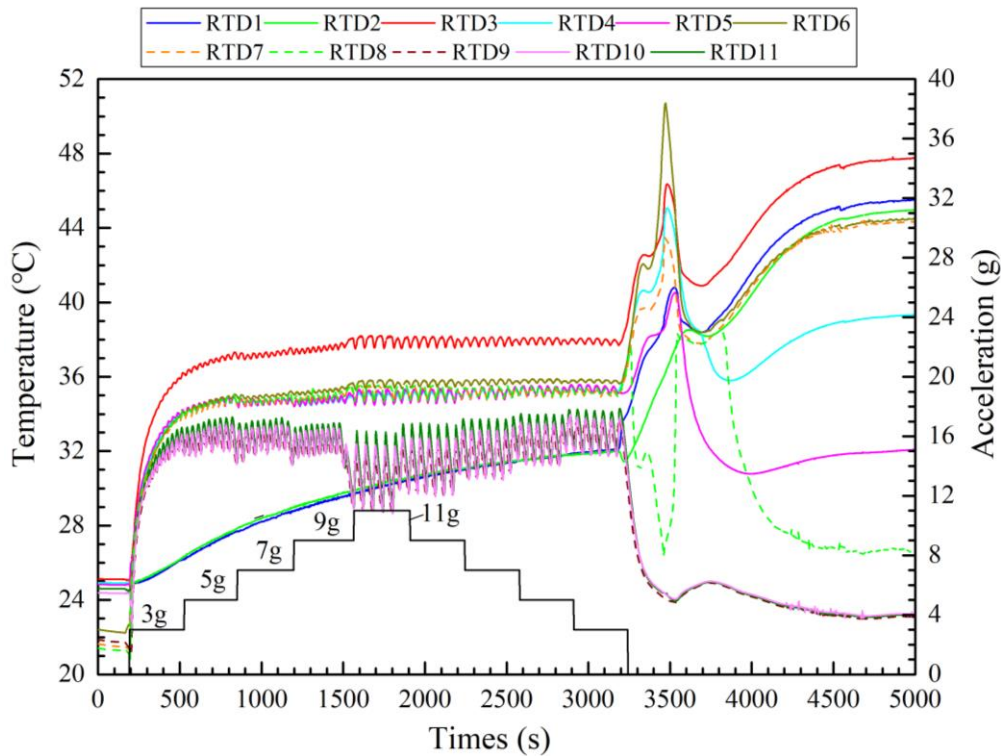


489
 490 Fig.11 Temperature evolutions at 300 W, acceleration pattern 2 and loading mode 2 under
 491 configuration B.

492 After the periodic acceleration was removed at 3250 s, the evaporator, vapor line and CCs
 493 temperature curves presented a formation of an obvious peak. Especially for the vapor line
 494 temperature, its instant maximum value got to 50.8 °C. But the temperature of the liquid line
 495 formed a valley. The vapor-liquid interface located somewhere between RTD7 and RTD8
 496 according to their temperatures.

497 In the current study, it was found that the temperature overshooting also appeared in the
 498 periodic acceleration pattern 2 and 3 at 250W with the same loading mode. To be sure, the

499 temperature overshooting under these conditions was negative for the operation of the
 500 DCCLHP. The reason for this result could be the variation of the pressure difference in the
 501 external loop and the redistribution of the working fluid in the entire loop after unloading
 502 acceleration force. As a consequence, the heat leak from the evaporator to CCs and the
 503 evaporator temperature increased rapidly.

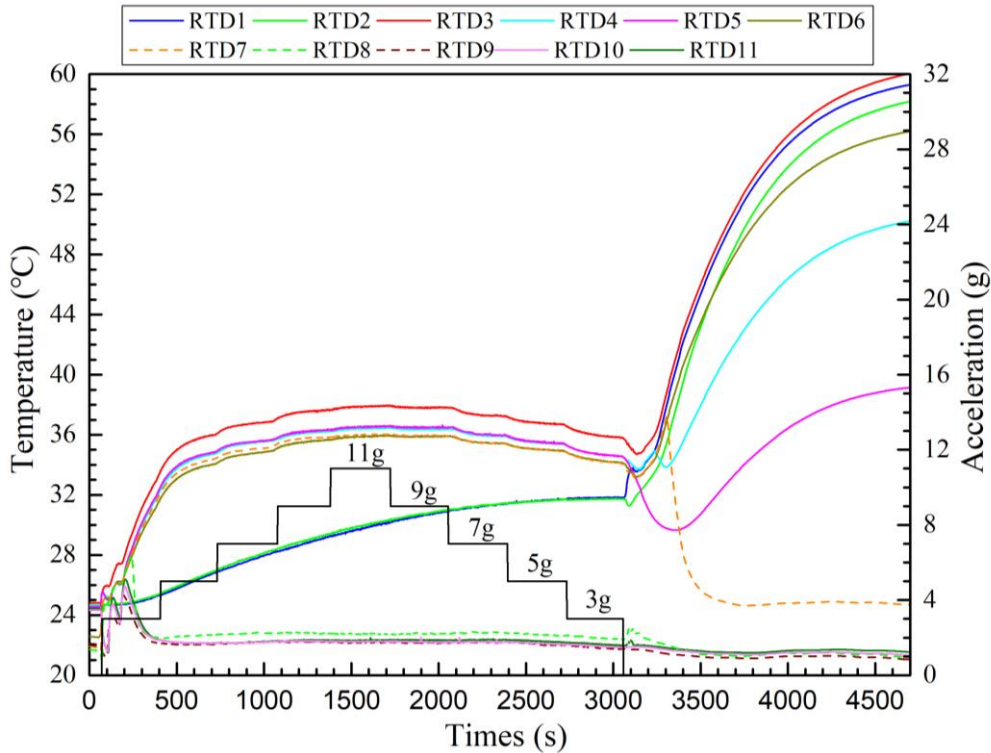


504
 505 Fig.12 Temperature variations at 300 W, acceleration pattern 3 and loading mode 2 under
 506 configuration B.

507 Fig.13 depicts temperature evolutions at 150 W, acceleration pattern 3 and loading mode 2
 508 under configuration B. The data in Fig. 13 indicates that there was no temperature overshooting
 509 after unloading the periodic acceleration. The temperature variation at periodic acceleration
 510 pattern 2 was similar to that shown in Fig. 13 under 150 W, loading mode 2 and configuration
 511 B. The temperature overshooting might be related to the magnitude of the heat load. The larger
 512 the heat load was, more likely the temperature overshooting occurred.

513 During the periodic acceleration, the temperature of RTD3 to RTD7 showed slightly stepped
 514 changes along with stepped increase and decrease of the acceleration force. However, the
 515 temperature of the CC1 and liquid line had no stepped changes. The highest temperature of the
 516 evaporator reached 37.9 °C when the acceleration was 11 g. The vapor-liquid interface located

517 somewhere between RTD7 and RTD8 point. After the acceleration force was removed at 3058s,
 518 the evaporator temperature descended firstly and then rose continuously to approximately 6 °C.
 519 Moreover, the vapor-liquid interface located somewhere between RTD6 and RTD7 point.



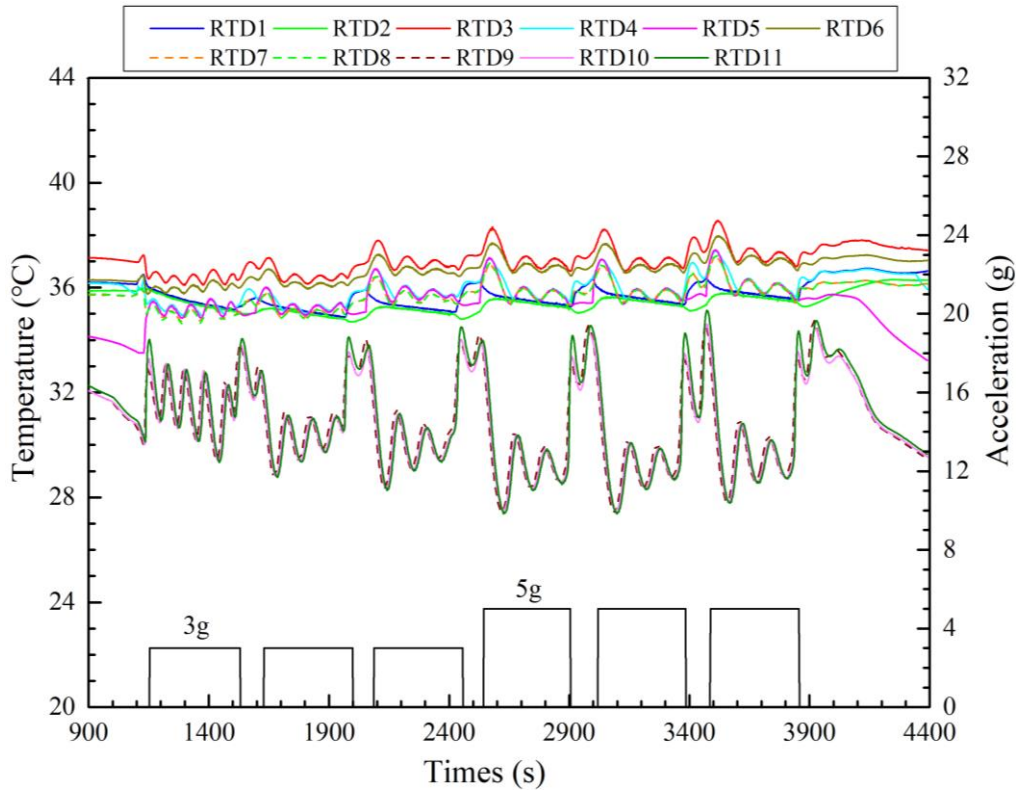
520
 521 Fig.13 Temperature evolutions at 150 W, acceleration pattern 3 and loading mode 2 under
 522 configuration B.

523 *3.4 Temperature oscillation*

524 Besides the periodic change of the loop temperature along with the periodic acceleration
 525 force changing, temperature oscillations of the loop during each periodic acceleration were
 526 observed in many cases, such as the cases of periodic acceleration pattern 2 or 3 and loading
 527 mode 2 at 250 W under configuration A, as well as periodic acceleration pattern 1 or 2 and
 528 loading mode 1 at 300 W under configuration B.

529 Fig. 14 illustrates the loop temperature curves at 300 W, periodic acceleration pattern 1 and
 530 loading mode 1 under configuration B. As can be clearly seen from the figure, all the loop
 531 temperature except for CC1 temperature showed obvious oscillations during the periodic
 532 acceleration force acting. The evaporator temperature at 5 g periodic acceleration was slightly
 533 higher than that at 3 g periodic acceleration. The temperature amplitude of the liquid line was
 534 greater than that of other loop components. The temperature change of the loop was the largest

535 between both periodic accelerations.



536
537 Fig.14 Temperature profiles at 300 W, acceleration pattern 1 and loading mode 1 under
538 configuration B.

539 It could be confirmed that the effect of the acceleration force led to the temperature
540 oscillation of the loop. The reason could be as follows. The tangential and radial acceleration
541 force changed the vapor-liquid distribution in the loop immediately once it was applied. The
542 heat leak from the evaporator to CC1 reduced but that to CC2 increased a bit. Simultaneously,
543 the pressure head originated from the acceleration force would decrease as the vapor-liquid
544 interface in the condenser moved forward by the increase of the RTD9, RTD10 and RTD11
545 temperatures. When the RTD9 temperature reached a peak value at about 1138 s, the
546 acceleration pressure head might arrive the smallest value. The capillary pressure difference
547 decreased to the smallest value to balance the loop pressure, which required the RTD4
548 temperature to drop to a valley value. Simultaneously, the evaporator temperature also
549 decreased and reached a valley value. When the subcooling of the returning liquid could not
550 balance the heat leak, the CC2 temperature stopped to drop and started to rise.

551 During the following fluctuation period, the vapor-liquid interface started to move backward
552 in the condenser. Therefore, the additional liquid in the CCs took over the space left by the

553 vapor recession through the bayonet. As the interface moved backward in the condenser, the
554 acceleration pressure head increased gradually. Correspondingly, the capillary pressure
555 difference increased to balance the loop pressure. The RTD4 temperature rose. In this process,
556 there was a phase difference between RTD4 and RTD9 temperature. Subsequently, the RTD4
557 temperature rose to a peak value and then dropped back to a valley value. On the contrary, the
558 RTD9 temperature decreased to a valley value and then increased to a peak value. At this time,
559 the phase difference of the RTD4 and RTD9 temperature disappeared. Then the next cycle of
560 the loop started. As a result, the sustained variation of the external loop pressure and the
561 capillary pressure self-regulation were the essential cause for the temperature oscillation.

562 In addition, the similar temperature oscillations during each acceleration force acting had
563 been presented in Fig. 11 and Fig. 12. There were significant distinctions in frequency and
564 amplitude between Fig. 11 and Fig. 12 and Fig. 14. It could be caused by the different loading
565 modes and periodic acceleration patterns.

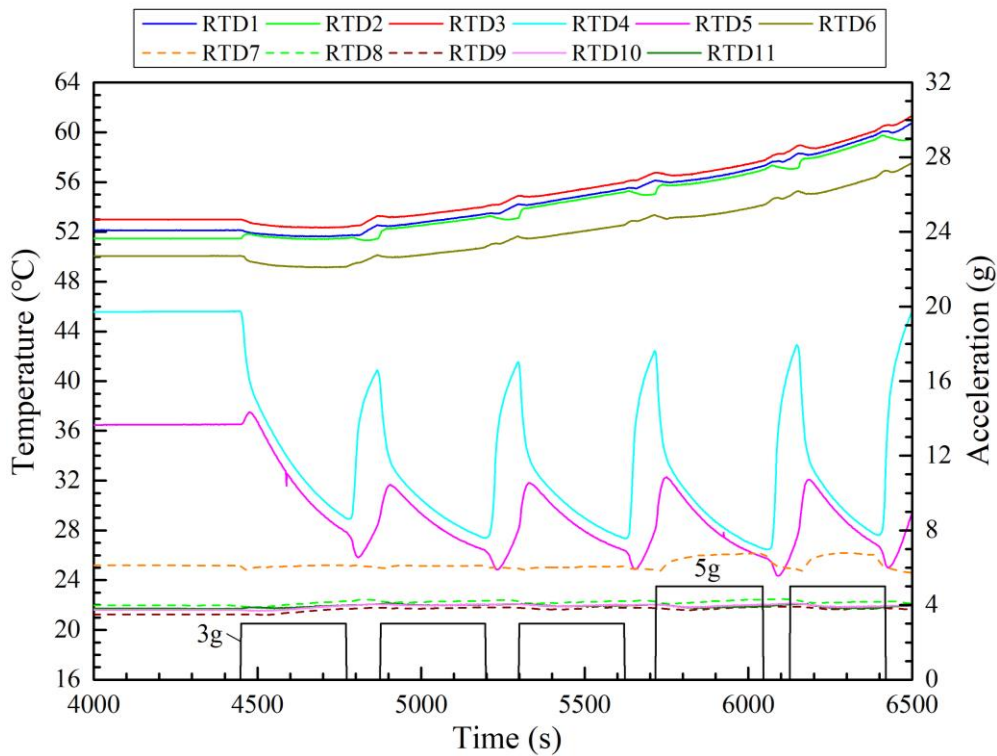
566 *3.5 Excessive operating temperature*

567 In some cases, the operating temperature of the DCCLHP continued to increase and finally
568 exceeded the maximum allowable temperature since the periodic acceleration was applied.
569 Moreover, the excessive operating temperature occurred only at the heat load of 150 W under
570 configuration A.

571 Fig.15 depicts the temperature curves at 150 W, periodic acceleration pattern 1 and loading
572 mode 1 under configuration A. It could be clearly seen from Fig. 15 that the loop temperature
573 showed a periodic fluctuation during the periodic acceleration. The CC2 temperature presented
574 more significant fluctuation than other components' temperature. The temperature of the CC1,
575 evaporator and vapor line increased gradually during the periodic acceleration acting.

576 The stable operating temperature was 53 °C in terrestrial gravity and the vapor-liquid
577 interface in the condenser located somewhere between RTD6 and RTD7. When the first 3 g
578 was applied, the liquid with lower temperature filled into the CC2 while the vapor entered into
579 the CC1. The vapor-liquid distribution in the CCs led to an increase of the heat leak from the
580 evaporator to CC1 but a decrease to CC2. However, the subcooling of the returning liquid
581 barely changed. Thus, the CC2 temperature dropped and the CC1 temperature rose in general.

582 In addition, the acceleration pressure head resulted in the decrease of the external pressure drop.
 583 Therefore, the capillary pressure difference reduced. The role of both effects determined the
 584 temperature of the evaporator and CC1 descending slightly. After unloading the first 3 g, the
 585 RTD4 temperature rose sharply. The RTD5 temperature decreased first and followed by a rapid
 586 increase. The temperature change was caused by the vapor-liquid redistribution in the CCs.
 587 Additionally, the external loop pressure drop increased which consequently led to a
 588 temperature increase of the evaporator and CC1. When the acceleration increased to 5 g, the
 589 amplitude of the CC2 temperature became much larger than that at 3 g. Furthermore, the RTD7
 590 temperature increased at 5 g. It indicates that the vapor-liquid interface moved forward in the
 591 condenser. Finally, the operating temperature exceeded the safety temperature limit.

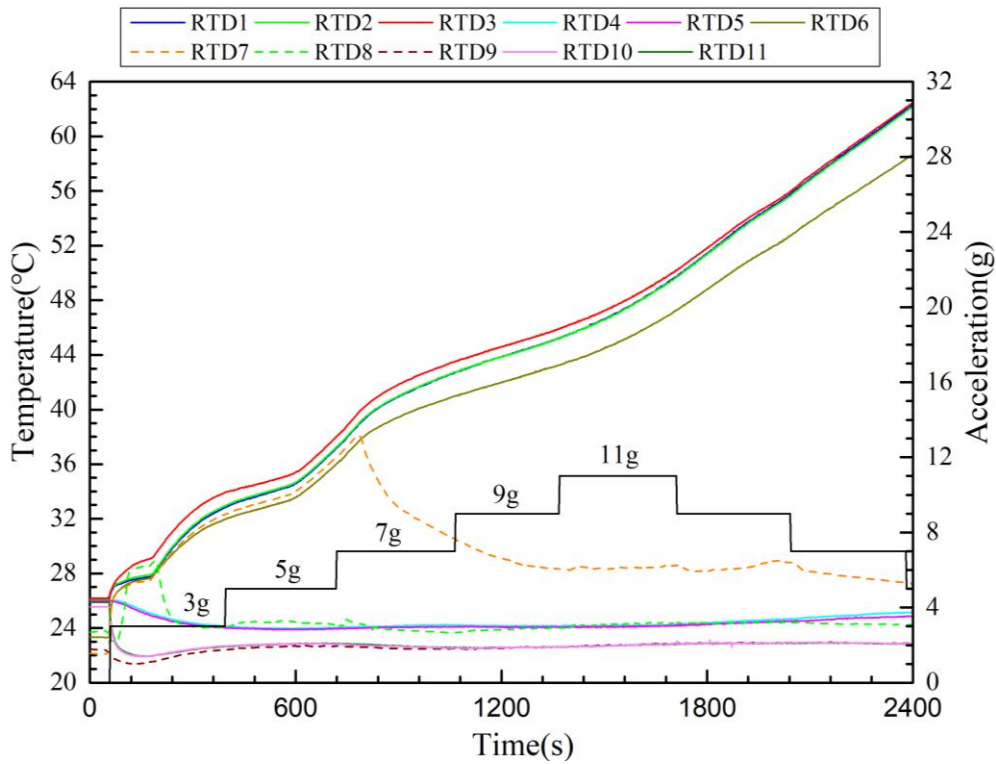


592
 593 Fig.15 Temperature profiles at 150 W, acceleration pattern 1 and loading mode 1 under
 594 configuration A.

595 Fig.16 displays the temperature curves at 150 W, periodic acceleration pattern 3 and loading
 596 mode 2 under configuration A. It demonstrates that the evaporator temperature continuously
 597 increased to 62.9 °C. At loading mode 2, the effect of the acceleration force made the CC2 be
 598 filled by liquid but the CC1 be filled by vapor. Thereby the heat leak from the evaporator to
 599 CC2 decreased but that to CC1 increased. The subcooling of the returning liquid remained

600 constant because the RTD9 temperature was constant. As a consequence, the temperature of the
 601 evaporator and CC1 would rise. Moreover, the acceleration pressure head changed along with
 602 the vapor-liquid interface moving backward. The evaporator and CC1 temperature
 603 continuously increased to regulate the capillary pressure force and further to balance the
 604 external loop pressure drop. Meanwhile, the heat leak needed to be balanced by the subcooling
 605 of the returning liquid. Finally, the loop failed to reach a steady state.

606 In the current work, excessive operating temperature was observed only at 150 W under
 607 configuration A. It indicated that the phenomenon would be related to the magnitude of the
 608 heat load and acceleration direction.



609
 610 Fig.16 Temperature profiles at 150 W, acceleration pattern 3 and loading mode 2 under
 611 configuration A.

612 **4. Conclusions**

613 The operating characteristics of the DCCLHP under periodic acceleration conditions were
 614 investigated experimentally in detail. Different heat loads, periodic acceleration patterns,
 615 loading modes and acceleration directions were systematically analyzed. The main conclusions
 616 are summarized as follows:

- 617 (1) During the period of periodic acceleration, the loop temperature periodically oscillated

618 with the acceleration periodic change. The temperature oscillation at the acceleration pattern 1
619 was more obvious than that at the acceleration pattern 2 and 3. The higher the acceleration
620 magnitude, the higher the operating temperature. For a given loading mode, heat load and
621 acceleration pattern, the maximum operating temperature under configuration A was greater
622 than that below 40 °C under configuration B. The maximum operating temperature dropped
623 with the heat load increasing under configuration A. But it dropped firstly and then rose under
624 configuration B. The maximum operating temperature at the acceleration pattern 3 was the
625 greatest among the three studied patterns.

626 (2) For the loading mode 1, the stable operating temperature difference and thermal
627 resistance under configuration B occurred randomly between before and after the periodic
628 acceleration force acting. Moreover, the stable operating temperature increased under the most
629 working cases, especially at 250 W and 300 W after removing the acceleration. For the loading
630 mode 2, there was a temperature overshooting after unloading, which could cause the operating
631 temperature exceeding 60 °C. The larger the heat load was, more likely the temperature
632 overshooting occurred. Both observed phenomena could be explained by the change of the
633 loop vapor-liquid distribution and the heat leak from the evaporator to the CCs.

634 (3) The loop temperature during each periodic acceleration showed obvious oscillation along
635 with varying the frequency and amplitude in some cases of 250 W and 300 W. The sustained
636 variation of the external loop pressure and the capillary pressure self-regulation were the
637 essential cause for the temperature oscillations. For several cases of 150 W under configuration
638 A, the excessive operating temperature could appear and even more than 60 °C, which would
639 be related to the heat load and the acceleration direction.

640 In this study, we demonstrated the operating performance including the above discussed four
641 kinds of particular phenomena, which are the essential factors that must be considered for the
642 DCCLHP system in practical applications. The corresponding analysis and possible mechanism
643 explanation are proposed for the first time, with potential significance of paving a foundation
644 to solve the critical problems of the DCCLHP. Investigating feasible strategies to address such
645 problems is the focus of our further research.

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