

不同蒸发器结构的超薄平板环路热管的传热性能的差异化

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2016-06-11 收稿, 2016-07-23 修回, 2016-07-23 接受, 2016-09-12 网络版发表
新能源汽车用动力电池高性能的研究国际合作项目(2013DFG60080)资助

摘要 开发设计了两款无毛细结构的超薄型(1.5 mm厚)铜-水平板环路热管, 并对其多方位下热传输性能进行实验研究. 对比分析了两种蒸发器结构的热管在不同角度下的启动能力和运行特性, 且探究了蒸发器结构对于超薄环路热管运行稳定性的影响, 以及热管性能在多方位条件下的差异. 实验表明两种结构热管均能满足多方位工作的要求, 具有抗重力特性, 其中平行四边形的结构设计有助于抑制流动不稳定, 抗重力性能更优, 不仅能够在 15° 时启动, 而且不同角度下热传输性能的差异仅为4%.

关键词 超薄, 热传输性能, 多方位, 差异, 运行稳定性

环路热管(loop heat pipe, LHP)是一种高效的相变传热装置, 由汽液传输管路连成回路, 并利用工质的相变来传递热量^[1], 具有汽液管路分离、蒸发器和补偿器一体化等结构特点, 从而决定了其汽液携带阻力小、启动快速灵活、多方位长距离传输热量的传热特点. 随着电子散热的迅速发展, 能与电子元件表面紧密贴合的微小型平板环路热管受到关注^[2,3]. 但传统环路热管热传输能力的提升受制于毛细芯结构的发展, 毛细结构要求既要具备较高的毛细极限又要保证较低的流动阻力^[4,5], 且毛细芯容易引起漏热, 增加LHP的低温启动难度. 而毛细芯结构通常较厚重, Kiseev等人^[6]实验发现多孔毛细芯厚度在5~7 mm时蒸发器效果最优. 而利用微小通道作为强化换热手段一直被广泛关注, 利用微小通道强化传热的特性, 结合环路热管汽液分离的结构特点, 在蒸发器内用微小槽道组替代毛细芯, 开发设计了新型的超薄平板环路热管^[7](ultra-thin looped heat pipe, ULHP),

其性能及应用亟待深入探讨. 类似形式的热管有分离式虹吸管(two-phase loop thermosyphon), 但目前所报道的虹吸管基本都是考查其在垂直条件下的工作特性^[8~11], 并不像LHP具有多方位运输的特点. 因此, 考查超薄平板热管在不同角度下是否能正常工作及其工作能力如何对ULHP的实际应用具有重要指导意义.

微小通道内流动沸腾的基础研究发展很快, 包括其内的两相流流型研究^[12~17], 传热机理研究^[18~22]以及压降研究^[23~26]等. 对于微小通道流动沸腾的应用研究, 最主要的挑战是由于通道限制, 气泡变形过快引发的温度/压力波动和流动不稳定性^[27]. 流动不稳定性对设备、装置的影响极大, 通道中原有的流体动力学状态被破坏, 换热系数变化, 传热性能急剧下降, 导致临界热流量提前来临(pre-critical heat flux), 造成局部烧干, 引起瞬时表面温度的飙升和压力的大幅波动. 特别是在水平和小角度放置时, 流动

引用格式: 洪思慧, 唐永乐, 张新强, 等. 不同蒸发器结构的超薄平板环路热管的传热性能的差异化. 科学通报, 2017, 62: 721~729

Hong S H, Tang Y L, Zhang X Q, et al. Multiple orientations research on heat transfer capabilities of ultra-thin loop heat pipes with various channel configurations (in Chinese). Chin Sci Bull, 2017, 62: 721~729, doi: 10.1360/N972016-00036

不稳定现象更为严重. 主动考虑并有效抑制流动不稳定性能够提高临界热流量, 强化换热系数, 保证系统的稳定工作. 目前, 减小微小通道内流动不稳定性的方法主要有对入口结构的限制式设计^[28], 设置扩张型微通道^[29], 人为增加汽化核心^[30]等.

针对可多方位工作的超薄平板环路热管, 其蒸发器内的微小通道在起到强化传热的作用同时, 也会带来流动不稳定性和压力、温度的波动, 引发传热性能的衰退, 尤其是因角度变化导致不稳定性加剧而引发的性能差异将限制ULHP的实际应用范围. 因此, 本文针对解决流动不稳定性以促进超薄环路热管内工质的循环效率为目的, 设计了槽道排布呈平行四边形和槽道排布呈梯形的两种蒸发器结构的ULHPs, 并在不同角度下全面考查两者热传输性能的差异, 及其对于抑制流动不稳定性的有效性, 得出这两种超薄型环路热管抗重力条件下的工作性能, 并验证了环路热管轻薄化的有效性.

1 实验系统

本文所研究的环路热管如图1所示, 其蒸发器为平板结构, 总厚度是1.5 mm. 蒸发器与外环路管线均由铜制成, 系统以水作为工质, 具体的结构参数见表1. 此外, 实验系统还由加热装置、冷凝装置、数据采集装置和固定装置等四部分联合组成. 加热装置由开有沟槽的承载台、三根加热铜棒以及与蒸发器大小相同的薄铜片. 铜棒放置于承载台的沟槽内, 由直流稳压电源(兆信KXN-645D)进行加热, 与薄铜片通过压条紧密贴合作为热源, 并紧贴蒸发器表面,

保证受热的均一性. 冷凝装置包括翅片组、风道、风扇(PF70201V1-000C-A99), 采用直流稳压电源(兆信KXN-645D)控制风扇的功率, 通过风道冷却翅片组进而实现冷却效果. 数据采集装置由安捷伦34970 A和温度采集模块01对环路的各部位共13个布温点, 使用K-OMEGA热电偶(精度为 $\pm 0.5^\circ\text{C}$)进行数据变动记录. 外环路总长度为445 mm, 冷凝部的长度为160 mm. 固定装置包括可调支架台, 加热部压条等. 实验系统垂直放置, 依靠重力解决无毛细回流问题. 加热功率的变化通过调节直流稳压电源的电压实现, 冷凝能力的大小通过调节风扇的输入电压进行调节. 热管样品及其内部微槽结构见图1, 实验台的示意图及实景图参见图2.

所做实验均在环境温度为 24°C 的条件下进行, 环境温度由室内空调设定和控制. ULHP外环路管线和蒸发器表面都包裹石棉网以减小漏热, 该石棉网

表1 超薄型环路热管的结构参数

Table 1 The structure parameters of ULHP

参数	值
蒸发器的长 $\times$ 宽 $\times$ 高	160 mm $\times$ 115 mm $\times$ 1.5 mm
蒸发器内槽道长 $\times$ 宽 $\times$ 高	105 mm $\times$ 3 mm $\times$ 0.6 mm
蒸发器内槽道间距	3 mm
蒸发器内槽道数	25 条
蒸发器壁材	铜
外环路总长度	445 mm
管线的内径/外径	2.4 mm / 3 mm
工质	水
工质充装量	5.0 g

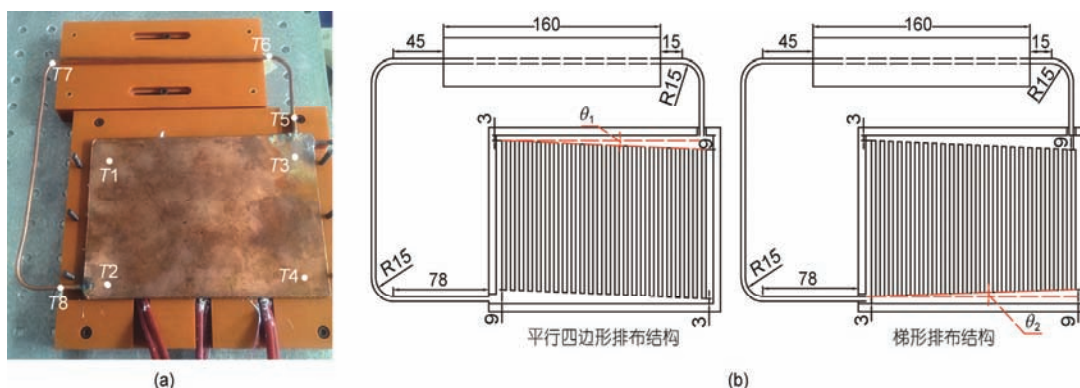


图1 (网络版彩色)热管样品及其内部槽道结构. (a) 样品实物; (b) 内部槽道结构

Figure 1 (Color online) The structure of the designed samples of ULHP. (a) The ULHP prototype; (b) the schematic diagram of channel configurations (parallelogram & trapezoid)

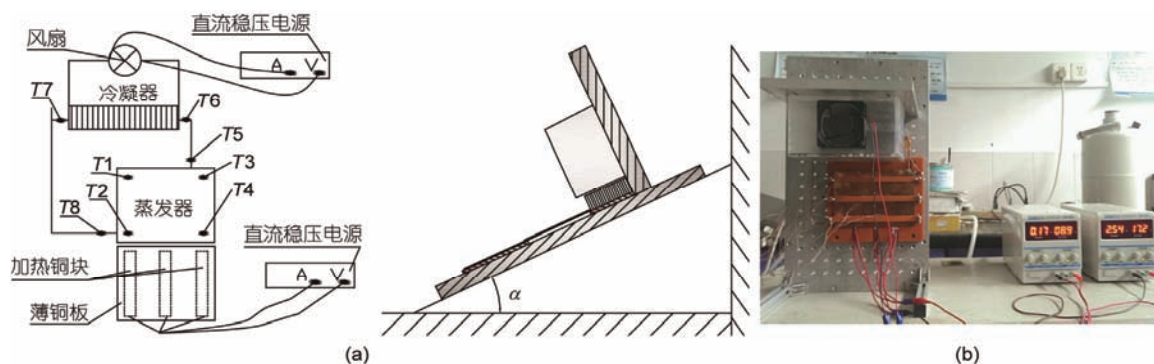


图2 (网络版彩色)实验台示意图及实物图。(a) 实验系统示意图;(b) 实验台实景

Figure 2 (Color online) The experimental set-up schematic diagram and apparatus. (a) Schematic diagram of experimental set-up; (b) experimental apparatus

的热导率为 0.034 W/(K m) 。另外, 加热铜板和冷凝器下方均垫有枕木, 枕木的导热系数为 0.051 W/(K m) , 在支撑部件的同时也能有效减小热管向金属支架的漏热。经多次实验并计算验证, 每次实验的总热损小于2%。实验过程不可避免存在实验误差, 根据《中华人民共和国国家计量技术规范JJF1059-1999》, 实验中直接观测的测量值不确定可由A类不确定度分析给出, 对于同一条件下的实验采用多次重复测试的手段, 保证实验现象的可重复性和有效性, A类不确定度由 $U(T_i) = \sqrt{\frac{1}{m(n-1)} \sum_{j=1}^m \sum_{i=1}^n (T_{ij} - \bar{T}_i)^2}$ 计算, 则温度值的最大不确定性计算得到为 1.83°C 。由仪器带来的不确定性可由B类不确定度给出, $U(X_i) = a/k$, 其中, a 是说明书上标称的误差范围, k 是根据 X_i 的分布得到的包含因子。采用矩形分布估计, k 为 $\sqrt{3}$ 。因此在本实验中, 热电偶的测试不确定度为 $\pm 0.289^\circ\text{C}$, 由直流稳压电源提供的加热功率以及风扇功率的不确定性在5.77%以下, 环境温度的不确定性控制在 $\pm 0.8^\circ\text{C}$ 以内。

2 结果与讨论

2.1 启动特性

由于没有毛细芯, 超薄平板环路热管内部工质

运行的推动力依赖于重力和相变压差。非垂直条件下, 推动力减小, 蒸汽工质的单向循环流动难以保障, 启动难度增大, 甚至无法启动。因此, 对ULHP临界工作角度的确定, 实质是对该款热管最低工作能力的界定, ULHP启动的临界角度将限制其实际应用的广度。考察两种结构的ULHP在不同角度下的启动情况, 其结果如表2所示。

受内部结构的影响, 两种结构的ULHP在启动能力上有显著差异。槽道排布呈平行四边形结构的ULHP 15° 放置时已能够在 50 W 的热负荷下经 2600 s 左右启动, 但梯形结构ULHP水平放置时无法启动, 直到倾角增大至 30° 时才能正常工作, 且仍需 3000 s 的启动时间。对比来说, 各角度下平行四边形结构的启动都更迅速, 且启动所需的热负荷也更低, 说明内部工质的单向循环流动能够更快速更稳定地建立, 这得益于槽道呈平行四边形排布时在入口处形成的“液池”结构。

工质是否形成单向循环可由冷凝器入口处 T_6 和蒸发器入口处 T_8 的温度差反映。即 $\Delta T_{6-8} = T_{e6} - T_{e8}$ 。 ΔT_{6-8} 的波动, 反映的是内部工质的不断振荡, 当系统启动, ΔT_{6-8} 应为正值且不断增大而波动逐渐减少。图3是两种结构的ULHP在临界角度下的启动特性曲线。根据上述分析, 平行四边形的ULHP在水平放置

表2 各角度下两种结构ULHP的启动功率和启动时间对比

Table 2 The heat loads and durations for the two ULHP samples to start-up

结构	0°	15°	30°	45°	60°	90°
平行四边形	/	40 W/2614 s	30 W/2350 s	30 W/2158 s	30 W/1880 s	30 W/700 s
梯形	/	/	40 W/2996 s	40 W/2630 s	30 W/2546 s	30 W/1600 s

时启动响应快, ΔT_{6-8} 的正向温差迅速增大, 约600 s时建立, 但此时工质的热动力不足, 启动不稳定, 至2600 s时, 系统完全启动. 而梯形ULHP的漏热严重, 启动响应慢, ΔT_{6-8} 的正向温差直到1100 s左右才形成, 此后也经历不稳定过程, 但波动幅度较大, 两相流工质反冲严重, 直到2996 s, 系统的正向循环才完全建立.

2.2 蒸发器平均温度

由于两种结构的ULHP在30°以后均能启动并稳定工作, 故文中后续对其他热传输性能的差异化进行比较时, 选取放置角度在30°~90°范围内进行. 图4对比了两种结构的ULHP在不同角度下各自的蒸发器平均温度随热负荷的变化规律. 很明显, 对于槽道形状呈平行四边形排布的ULHP, 蒸发器平均温度随放置角度的变化不大, 倾斜角在30°~60°区间内时, 温度的平均变化差异为4%; 即使与极限情况垂直放置时相比, 蒸发器平均温度的变化也不超过10%, 说明槽道排布呈平行四边形结构的ULHP具有良好的抗重力性能, 放置角度对其传热性能的影响较小. 而放置角度对梯形结构ULHP传热能力的影响则明显增加. 各角度下蒸发器平均温度相差较大, 由角度变化引起的平均差异约为7.8%, 而与垂直放置时的状况相比, 其温度变化的幅度高达20%.

图5对比了两种结构的ULHP的蒸发器平均温度

在不同放置角度下的具体差异, 反映的是角度对两者热传输性能差异的影响. 可以看出, 两种排布形状的ULHP的蒸发器温度差异随着角度的增大而显著减小, 垂直条件下, 两种结构的热传输性能差别很小, 启动后, 在100 W的热负荷范围内, 两者蒸发器平均温度几乎相同; 但在倾斜角度为30°时两者的最大温差达到9.11℃, 因此对比来说, 平行四边形的抗重力性能更好, 而梯形结构的ULHP的热传输能力随着角度的增加明显衰减.

2.3 运行稳定性

两种排布结构最大的区别就在于入口处形成的“液池”结构, 其作用在于减小蒸发器槽道内两相工质的流动不稳定性影响, 保证工质的单向稳定循环, 从而提高系统的传热性能. T_8 位于蒸发器入口处, 既受到回流冷液补充的影响, 又受到蒸发器漏热及其内工质反冲的影响, 是整个系统中温度波动最大, 运行最不稳定的位置. 对各角度下两种结构 T_8 处的温度波动情况进行分析, 能够进一步说明“液池”结构对于稳定工质的单向循环的效果. 图6(a)和(b)分别是平行四边形结构和梯形结构不同角度下 T_8 处的温度波动随热负荷的分布情况. 首先, 槽道呈平行四边形排布结构时, T_8 处的温度波动范围在 $\pm 6^\circ\text{C}$ 内, 而梯形结构下, 温度的波动范围明显扩大至 $\pm 12^\circ\text{C}$, 说明“液池”能够有效地抑制入口处的温度波动, 减小回流的

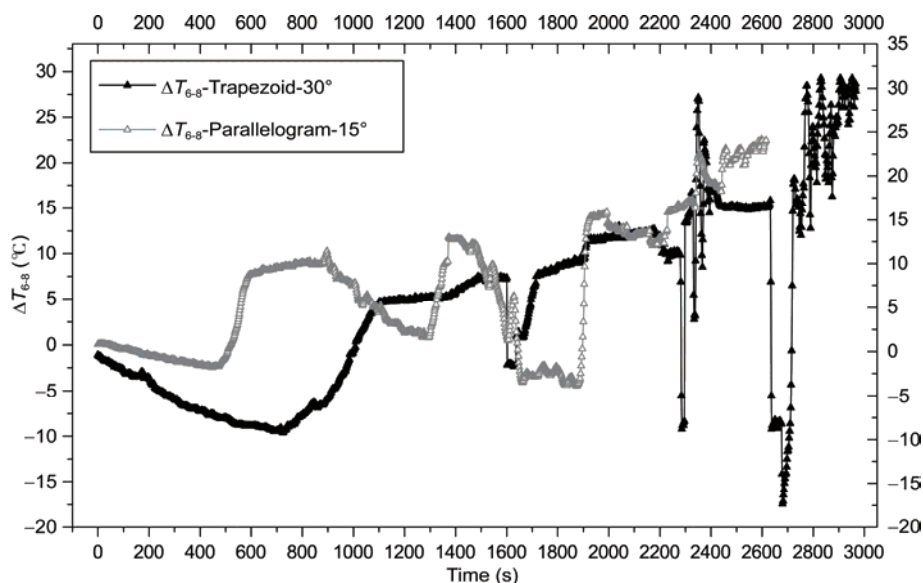


图3 临界角度下两种结构的ULHP的启动特性曲线

Figure 3 The start-up characteristic curves of two ULHP samples under the critical angles

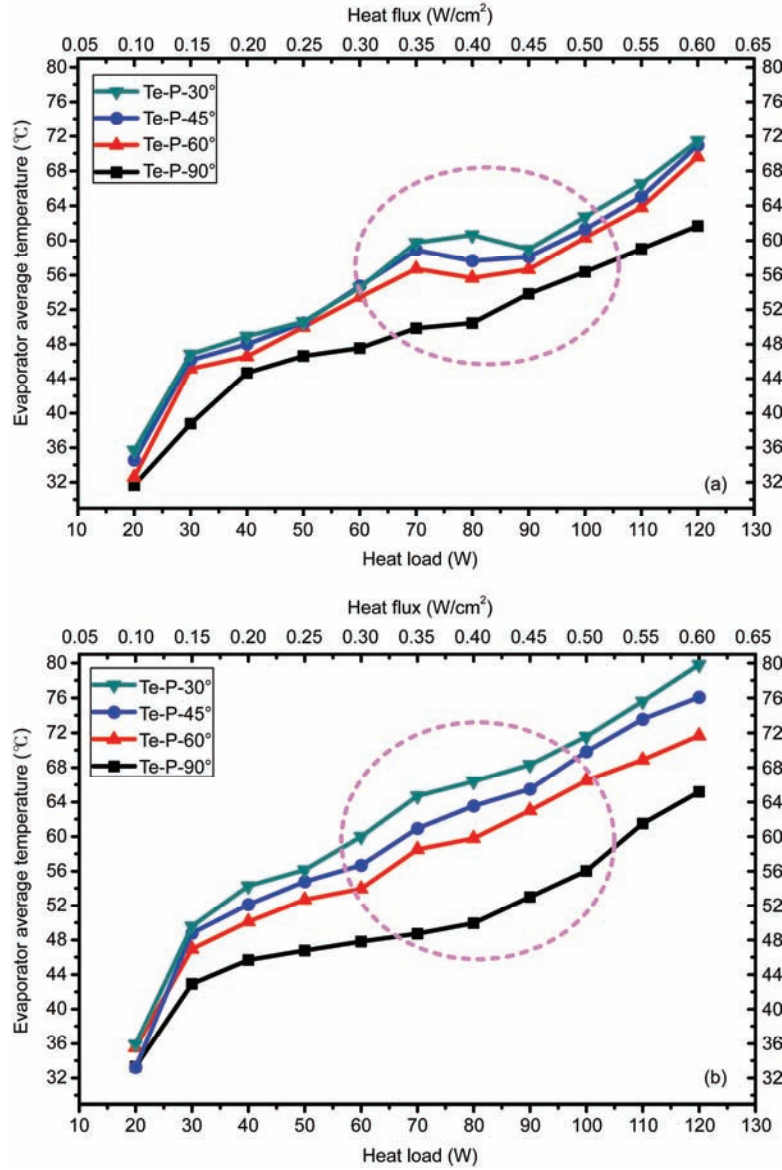


图4 (网络版彩色)不同角度下, 两种结构ULHP的蒸发器平均温度随热负荷的变化. (a) 平行四边形结构ULHP; (b) 梯形结构ULHP

Figure 4 (Color online) The variations of the evaporator average temperature of the two ULHP samples along with the heat loads under different orientations. (a) The parallelogram configuration; (b) the trapezoid configuration

冷液工质补充进入蒸发器的阻力, 且利于蒸气工质的加速流出, 即能抑制入口处流动不稳定性, 保证工质循环的稳定性和单向性. 其次, 对于平行四边形结构的ULHP, 其温度波动的变化随放置角度的变化并不大, 一致性较好, 抗重力能力强, 这也与上述讨论结果相吻合.

2.4 热阻

根据环路热管的工作特性和原理, 可定义平板

式环路热管的环路热阻为

$$R = (T_{\text{Evap}} - T_{\text{Cond}}) / Q_{\text{in}} \quad (1)$$

热阻是评价热管能力的直观指标, 上述对启动性能和蒸发器均温的讨论也可由热阻得到反映. 图7是两种结构下ULHP的热阻在不同角度下随热负荷的变化情况. 相比梯形结构的ULHP, 槽道分布呈平行四边形结构排布的ULHP的热阻明显较低, 平均低21%左右, 这是由于梯形结构入口处无“液池”的缓冲

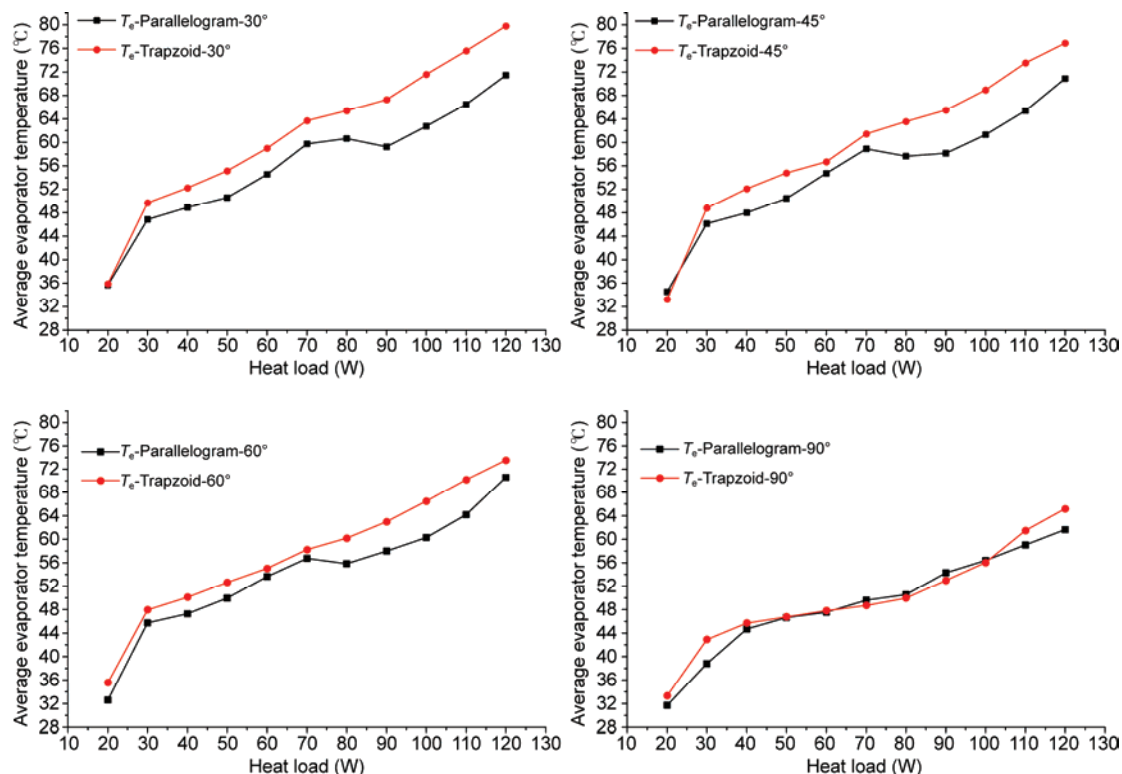


图5 (网络版彩色)两种结构下ULHP的蒸发器平均温度的差异随角度的变化

Figure 5 (Color online) The difference of evaporator average temperature between the two ULHP samples under different angles

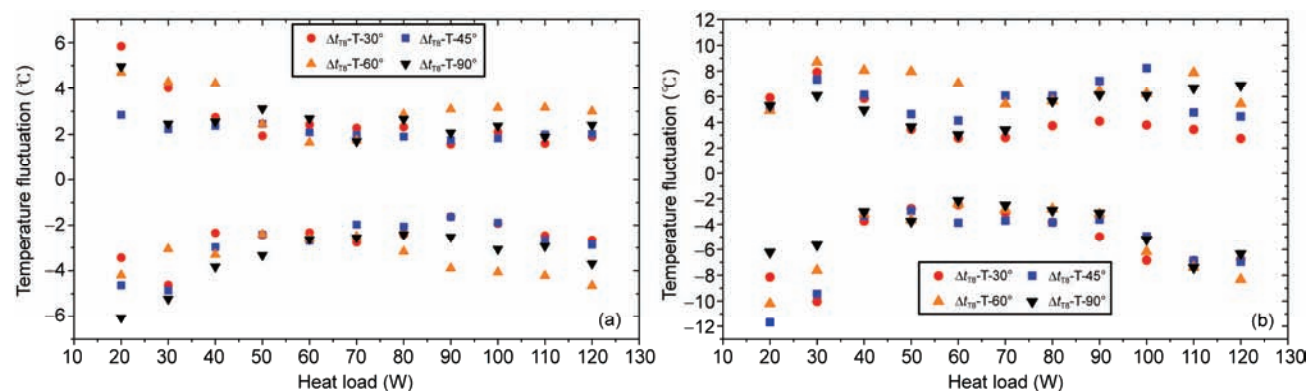


图6 (网络版彩色)不同角度下, T_8 处温度波动的差异. (a) 平行四边形结构ULHP; (b) 梯形结构ULHP

Figure 6 (Color online) The variations of temperature oscillation along with the angles for the two ULHP samples. (a) The parallelogram configuration; (b) the trapezoid configuration

作用, 梯形结构下工质的流动不稳定性现象加剧, 温度振荡频繁, 较难建立稳定的单向循环, 恶化了系统的传热能力. 梯形结构下ULHP的热传输性能受角度的影响更显著, 这一点也反映在热阻情况的对比中, 此结构下各角度下热阻的差值更大. 在垂直放置时, 作为驱动力的重力起决定性作用, 系统启动后, 两种结构下工质的循环都更为顺畅, ULHP的运行也更为

高效, 故此时其热阻都大幅降低但相差不大.

3 结论与展望

通过对两款具有不同蒸发器结构的超薄平板环路热管在不同角度下的热传输性能差异进行实验探究, 全面了解了这两种结构ULHP的性能, 明确了蒸发器的结构特点对于超薄平板环路热管运行过程,

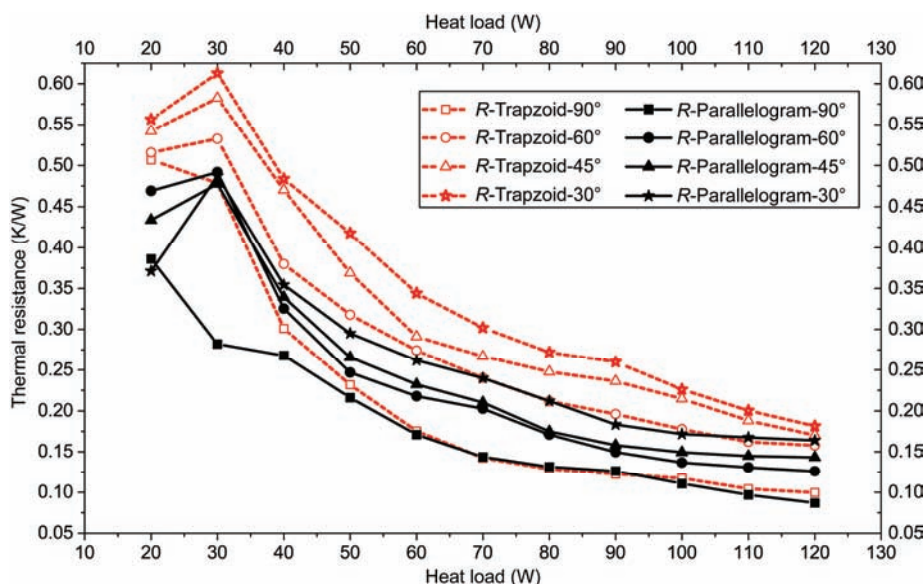


图7 (网络版彩色)两种结构下ULHP的热阻的差异随角度的变化

Figure 7 (Color online) Variations of thermal resistances along with heat loads for the two ULHP samples under different angles

即其内部工质流动与传热过程的影响,对超薄平板环路热管进一步的优化设计有指导意义,得到如下结论。

(1) 两种ULHP的临界工作角度不同。平行四边形结构下ULHP在15°时能够稳定启动并工作;梯形结构下ULHP的临界工作角度为30°。平行四边形的排布结构更有助于保证工质的单向循环流动,系统的启动响应更快。

(2) 两种ULHP的抗重力性能不一致。平行四边形结构的ULHP的抗重力性能更好,不同倾角下的热传输性能差异小,蒸发器平均温度的平均差异为4%,最大差异为10%;而梯形结构下的平均差异达到7.8%,最大差异扩大至20%。平行四边形结构的优越性在小角度下更为显著。

(3) 平行四边形排布时存在的“液池”结构对于削弱系统内工质的流动不稳定性起到重要作用,温度波动明显减小,系统能更快建立稳定的单向循环,

且循环效率提升,热传输能力增强。

符号说明

i	测试的次数
j	变量编号
k	分布因子
m	测试总数
n	变量总数
Q_{in}	输入热负荷W
R	热阻K/W
T_{evap}	蒸发器的平均温度,蒸发器表面个点 $T_1 \sim T_4$ 的温度平均值 $T_{evap} = (T_1 + T_2 + T_3 + T_4) / 4$ K
T_{cond}	冷凝器的平均温度,冷凝器进出口 T_6 和 T_7 的温度平均值 $T_{cond} = (T_6 + T_7) / 2$ K
U	不确定性
X	B类实验误差

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Summary for “不同蒸发器结构的超薄平板环路热管的传热性能的差异化”

Multiple orientations research on heat transfer capabilities of ultra-thin loop heat pipes with various channel configurations

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Battery thermal management system (BTMS) technology attracted more and more attentions as the new-energy automobile industry has gotten swift and violent progress in a few decades. So far, the widely used technologies include air cooling, liquid cooling and Phase Change Material (PCM) cooling. However, a common problem exists in all used technologies is the complex structures as well as the huge weight and volume, which not only increases the extra energy consuming, but also goes against the development requirement of automobile lighting. In the future, it is required without doubt that the battery thermal management system should be conveniently installed, light in weight and compact in volume, and minimized in secondary energy consumption. Thus, as a passive and effective heat transfer method, the heat pipe technology would be quite match the requirement and able to be further applied in BTMS.

In order to cater to the developed requirement of lightweight design in battery thermal management system, ultra-thin loop heat pipe (ULHP) prototypes with only 1.5 mm in thickness were developed. The ultra-thin design was achieved by replacing the traditional capillary core structure with micro channels, which however required extra assistance from the gravity for the ULHP system to operate, and brought about the risk of flow instability at the same time. To fully understand the exact effect of channel configuration on the heat transfer performance of ULHP, and conquer the adverse impact caused by flow boiling in micro channels, two different channel configurations inside the evaporator (parallelogram and trapezoid) were special developed and compared. Their dissimilarities in heat transfer characteristic were studied and compared under multi orientations with experiments, which could be divided into various aspects, the critical work angle, as well as the start-up characteristic, the thermal resistance and the flow instability et al, so as to completely reflect the respective influences of the parallelogram and trapezoid configurations on the operation and system stability of ULHP. The experiments results showed that both these two ULHP prototypes can work under small angles, meeting the demand of working under multiple orientations. Specially, the parallelogram evaporator configurations showed more superior performance with little gravity assistance by better suppressing the flow instability. This kind of ULHP could not only start up under 15° inclination, but also its average evaporator temperature difference between angles was limited in 4%, the largest difference was less than 10%. Nevertheless, the ULHP with trapezoid configuration couldn't work until the placed angles increased to 30°, while its average evaporator temperature difference between angles and the largest difference for the trapezoid one achieved 7.8% and 20% respectively. The parallelogram configuration made contribution on ensuring the one-way forward circulation of the working fluid inside ULHP, the response of start-up process therefore was faster. The “liquid pool” structure formed in parallelogram configuration also played an important role in decreasing the pressure and temperature fluctuation and easing the flow instability, which not only enhanced the heat transfer capability of ULHP, but also effectively reduced the damage to the battery system. BTMS could work more stably with ULHP whose channel configuration inside the evaporator was in parallelogram.

ultra-thin, heat transfer characteristic, multiple orientations, differences, operation stability

doi: 10.1360/N972016-00036