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不同肋片结构的印刷电路板换热器传热与阻力特性

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摘要 随着电子系统日益发展, 高热流密度电子器件的冷却问题备受关注, 微细通道液冷是一种广泛使用的高效冷却方式. 印刷电路板换热器具有传热系数高、紧凑、高效等特点, 有望成为微细通道热沉的备选方案. 为此, 本文对几种不同肋结构印刷电路板换热器的散热性能进行了评估, 结果表明, 非连续肋结构性能显著优于连续平直肋结构; 改进翼型肋综合传热性能最佳, 其次依次是翼型肋、椭圆肋、圆形肋和连续平直肋, 改进翼型肋在高雷诺数条件下优势更加显著; 相对于平直肋, 改进翼型肋印刷电路板换热器*Nu*数提高了20.2%, 阻力上升了5.6%.

关键词 电子器件散热, 印刷电路板换热器, 改进翼型肋片, 综合传热性能

随着计算机、电子芯片技术等行业的快速发展, 大功率集成化电子器件向更紧凑结构发展, 对于电子器件冷却的要求也越来越高[1]. 印刷电路板换热器(PCHE)由英国Heatric公司提出并已商业化生产[2], 其比表面积一般大于1500 m^2/m^3, 是一种高效紧凑的换热设备, 由于其紧凑度高、耐压、耐高温等特点, 通常应用于高温、高压或高热流密度等极端工况, 如跨临界制冷系统[3]、热泵系统[4]及布雷顿循环系统[5]等. 通过数值模拟方法可以对不同肋片结构进行分析, Hamid等人[6]研究了不同角度对Z型肋片印刷电路板换热器综合性能影响; Ma等人[7]分析了连续肋片印刷电路板换热器在高温条件下的传热阻力性能; Ngo等人[8]提出了非连续*S*型肋片, 可以有效提高印刷电路板换热器的综合性能; Lee和Kim[9]率先提出了翼型结构在印刷电路板换热器中的应用, 并分析其排列结构对传热的影响; Xu等人[10]提出一种形似剑鱼, 基于减阻设计的印刷电路板换热器改进翼型肋片.

本文将采用印刷电路板换热器, 以水为工质对高热流密度电子元件进行冷却, 研究了不同肋片结构对流动传热性能的影响, 分析对比流场及温度场, 提出性能更优的改进翼型肋结构印刷电路板换热器.

1 物理模型与边界条件

物理模型如图1所示, 该电子器件长为143.2 mm, 宽为30 mm, 散热表面的热流密度为6.05×10^5 W/m^2, 材质为紫铜; 换热工质为水, 入口温度为25℃, 工作压力为0.2 MPa. 电子器件上方布置单层流道印刷电路板换热器用以冷却散热, 建立了连续型肋、圆形肋、椭圆肋、翼型肋和改进翼型肋等5种肋片结构的印刷电路板换热器, 其结构尺寸如表1所示. 其中平直肋为连续型肋结构, 其各通道内部流动相对独立. 圆形肋、椭圆肋、翼型肋和改进翼型肋为非连续肋结构, 相邻流道之间的流体有掺混, 流动扰动更加强烈. 图2所示为计算模型的几何参数, 其中平直肋PCHE的流体横截面为直径2.0 mm的半圆形槽道, 3种非连续肋(圆形、椭圆形、翼型肋)结构尺寸如图3所示. 圆形肋结构流道的最小流通截面积与平直肋结构的最小流通截面积相等, 椭圆肋、翼型肋与圆形

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Chu W X, Li X H, Ma T, et al. Heat transfer and pressure drop performance of printed circuit heat exchanger with different fin structures (in Chinese). Chin Sci Bull, 2017, 62: 1788–1794, doi: 10.1360/N972016-00433

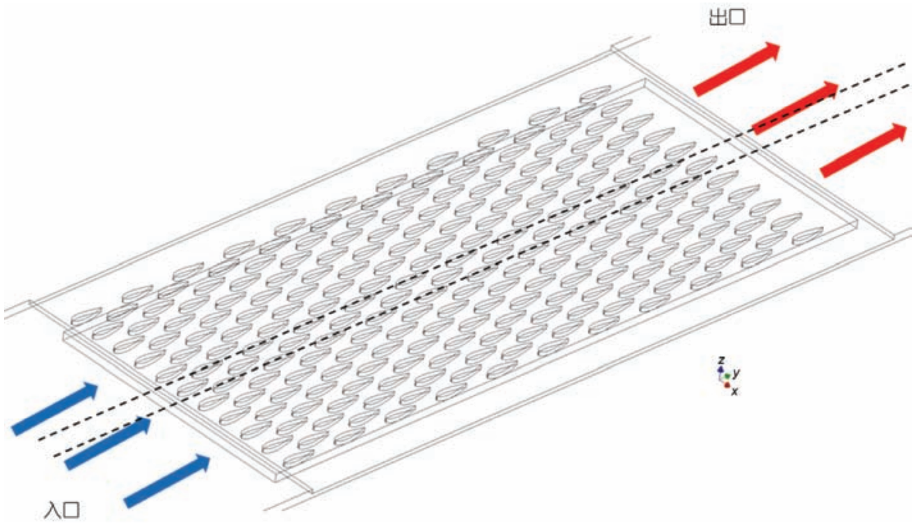

图 1 (网络版彩色)数值模拟的物理模型
Figure 1 (Color online) Physical model of numerical simulation

表 1 结构尺寸参数
Table 1 Geometric parameters

肋结构	入口宽度(mm)	通道直径(mm)	肋片高度(mm)	长度(mm)	排数
平直肋片	6.3	2	–	143.2	–
非连续肋片	6.3	–	0.88	143.2	20

图 2 印刷电路板换热器连续肋片与非连续肋片模型几何参数
Figure 2 Simulation models of PCHE with continuous and discontinuous fins

肋的周长相等. 翼型肋采用NACA0025标准翼型, 其长度为4 mm, 改进的翼型肋是取两个首尾相连的标准翼型肋的交集部分. 在本计算模型中, 电子元件上表面与印刷电路板换热器下表面接触, 电子元件发热, 热量通过导热过程由电子元件上表面向换热器内传导, 换热器内流体通过对流换热将热量带走. 该模型通道内肋分别采用连续的平直肋, 以及非连续的圆形肋、椭圆肋、翼型肋和改进的翼型肋结构, 整个换热器材质为紫铜. 由于宽度方向肋片数目较多, 因此宽度方向的边缘效应影响可以忽略[11], 为节省

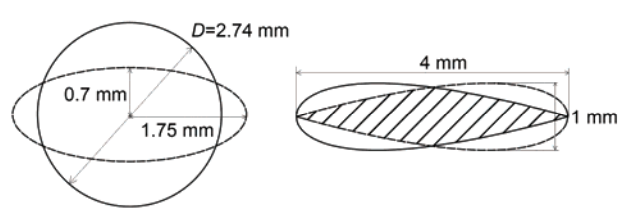

图 3 几种典型非连续肋片的几何参数
Figure 3 Geometrical parameters of discontinuous fins

计算空间, 数值模拟选取图1虚线部分作为计算区域, 边界条件设置如图4所示, 冷水由左侧入口进入, 通

过换热器后由右侧出口流出，两侧为对称边界，元件下表面为恒热流边界，上表面为绝热，整个计算区为流固耦合计算.

2 网格无关性与方法有效性验证

当量直径定义如下:

$$D_h = \frac{4A_c}{P}, \tag{1}$$

其中, D_h为通道当量直径，单位为m; A_c为最小流通截面积，单位为m^2; P为最小流通截面的周长，单位为m.

Reynolds数定义如下:

$$Re = \frac{\rho u_{max} D_h}{\mu}, \tag{2}$$

其中, Re为雷诺数, ρ为流体密度，单位为kg m^{-2}; u_{max}为流体在通道内最小流通截面的最大流速，单位为m s^{-1}; μ为流体动力黏度，单位为Pa s.

平均Nusselt数定义为

$$Nu = \frac{h \cdot D_h}{\lambda}, \tag{3}$$

其中, Nu为无量纲Nusselt数; h为平均对流传热系数，单位为W m^{-2} K^{-1}; λ为导热系数，单位为W m^{-1} K^{-1}.

本文采用商业软件CFX12.1进行数值模拟计算[12]，选取SST k-ω湍流模型[13]，该模型可以求解壁面附近边界层流动，对边界层网格的要求较高，模型网格划分的壁面第一层网格厚度为0.01 mm，计算结果的壁面y+满足模型的要求．采用QUICK方法对动量方程进行离散，控制残差为10^{-6}．如图5所示为改进翼型肋片结构的网格无关性验证，结果表明，当网格节点数大于186万时，其结果变化不到1%，因此选取186万网格节点进行计算，此时所采用的网格如图6所示．参照Xu等人[10]的研究工作来验证本文计算方法的可靠性，采用的流体工质和肋片结构与文献相同，数值模拟结果与文献结果对比如图7所示，可以看出，流体出口平均温度和单位长度阻力的计算误差均小于2%，因此验证了本文计算方法的可靠性.

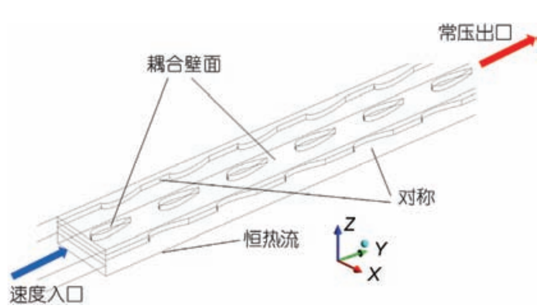

图 4 (网络版彩色)计算模型和边界条件设置

Figure 4 (Color online) Computational model and boundary conditions

3 结果与讨论

图8对比了连续平直肋与非连续圆形肋结构在不

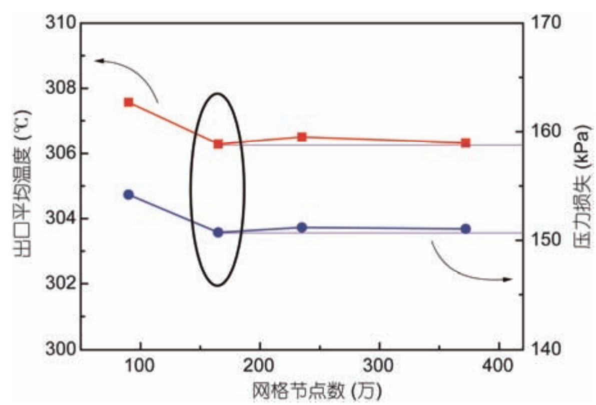

图 5 (网络版彩色)网格无关性验证

Figure 5 (Color online) Grid indepandence test

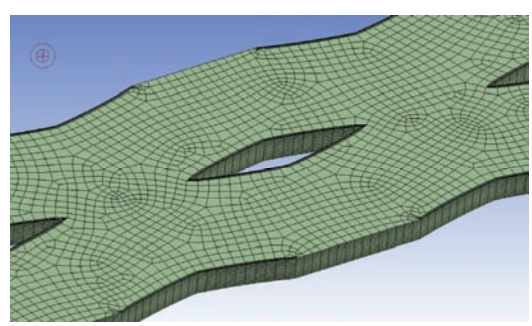

图 6 (网络版彩色)网格划分

Figure 6 (Color online) Schemetic of mesh generation

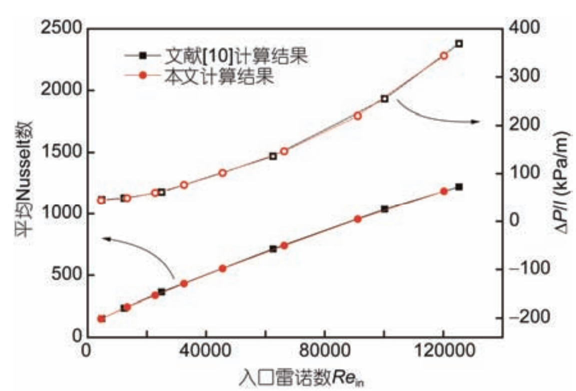

图 7 (网络版彩色)数值方法有效性验证

Figure 7 (Color online) Model validation

同雷诺数下的传热与阻力性能, 可以看出, 在相同雷诺数下采用圆形肋片时上壁面平均温度更低, 表明流体可以带走更多的热量, 同时圆形肋结构压力损失明显大于平直肋片, 主要是由于流体流过非连续肋时相邻通道的流体相互掺混, 受到下游肋片的碰撞产生扰流, 更有利于破坏边界层, 壁面热阻小从而使传热性能更强, 同时也增大了阻力. 图9为流体在平直肋片以及相邻两排圆形肋横截面的速度分布, 由于圆形肋错流布置, 圆形肋结构中流体在各截面的速度不断发生变化, 而平直肋结构中流体沿程最大流速的位置都位于通道中心.

相比于连续平直肋结构, 非连续肋结构表现出更好的传热性能, 优化非连续肋几何形状具有重要意义, 接下来分别对周长相同的圆形、椭圆形、翼型、改进翼型4种肋结构进行分析. 图10所示为流体沿程流线图, 可以看出流体在通过第9排肋达到充分发展. 随着肋形状趋向扁平, 进而趋向流线型, 尾部流线变平滑, 其中改进翼型肋时流速分布最均匀, 这是由于改进的翼型肋头部和尾部均为扁平状, 流体在撞击肋片前缘后得到平滑过渡, 这种肋片结构更有利于减阻.

如图11所示为几种肋结构的平均Nu数随Re数变化. 在相同Re数下对比, 平直肋结构传热性能最差; 在Re数较低时, 几种肋结构传热性能差别很小, 随着Re数逐渐升高差别逐渐增大, 流体扰动非连续肋的湍流特性增强, 相对于圆形肋、椭圆肋、翼型肋与改进翼型肋的Nu数分别提高了70.1%, 45.5%, 29.1%和20.2%. 从Nu数增大趋势可以看出, 若Re数沿已知

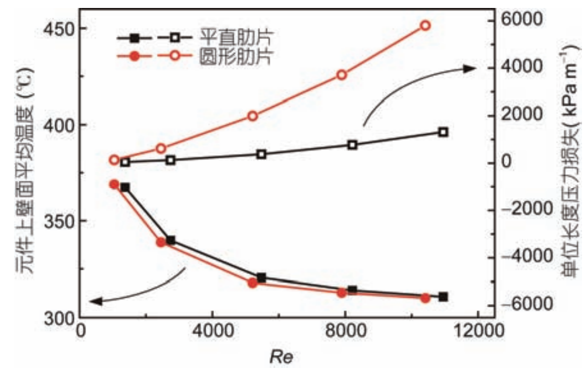

图 8 (网络版彩色)连续平直肋与非连续圆形肋壁面平均温度与压力损失对比 (m=1.0×10^{-2} kg/s)

Figure 8 (Color online) Average wall temperature distributions of PCHE with plain fins and circle fins (m=1.0×10^{-2} kg/s)

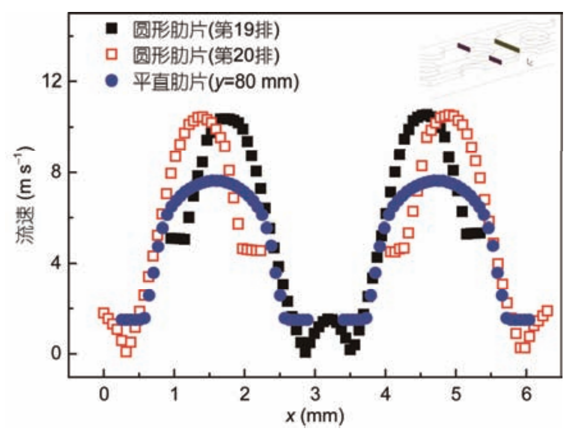

图 9 (网络版彩色)截面速度分布(m=1.0×10^{-2} kg/s)

Figure 9 (Color online) Velocity distribution of cross section (m=1.0×10^{-2} kg/s)

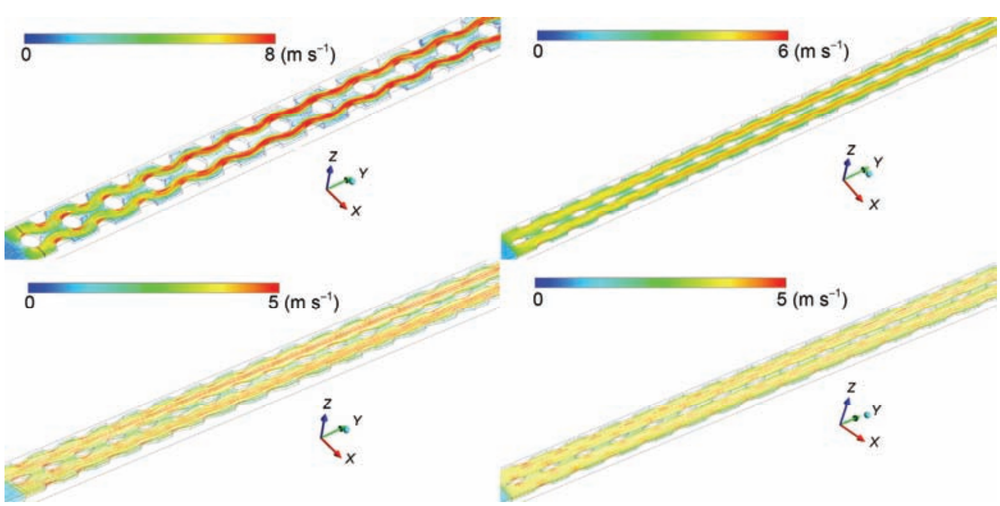

图 10 (网络版彩色)非连续肋结构流线图(m=1.0×10^{-2} kg/s)

Figure 10 (Color online) Streamline of PCHE with discontinuous fins (m=1.0×10^{-2} kg/s)

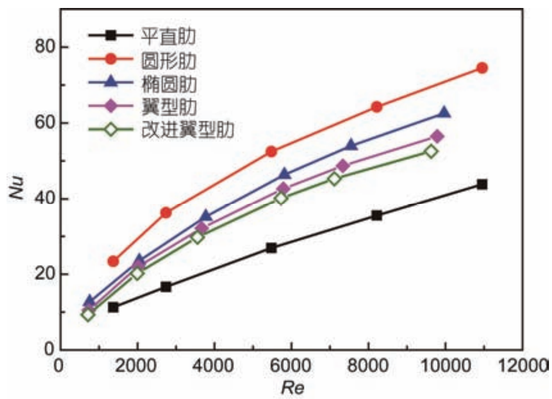

图 11 (网络版彩色)不同雷诺数下努塞尔数对比

Figure 11 (Color online) Comparision of Nusselt number at different Reynolds numbers

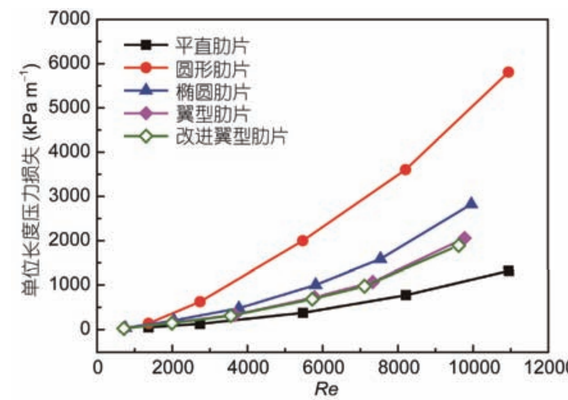

图 12 (网络版彩色)不同雷诺数下单位长度压力损失对比

Figure 12 (Color online) Comparision of pressure loss per unit length at different Reynolds numbers

曲线继续增大，*Nu*数的变化率逐渐降低，即增加流体进口流量，对传热性能的影响将越来越有限.

另一方面，从图12可以看出单位长度压力损失随*Re*数的变化. 4种非连续肋的阻力均大于连续的平直肋结构，这主要是由于非连续肋扰动更大；在相同*Re*数下，圆形肋的阻力最高，且随着*Re*数增加，单位长度压力损失呈二次关系增长. 以平直肋结构为参照，采用圆形肋、椭圆肋、翼型肋及改进翼型肋结构的压力损失最高上升了340%, 114%, 40.9%和5.6%. 4种非连续肋结构中改进翼型肋阻力增大幅度最小，主要原因是改进的翼型肋片前端与后缘均为尖角形，流体在肋前后横向速度梯度变化均匀.

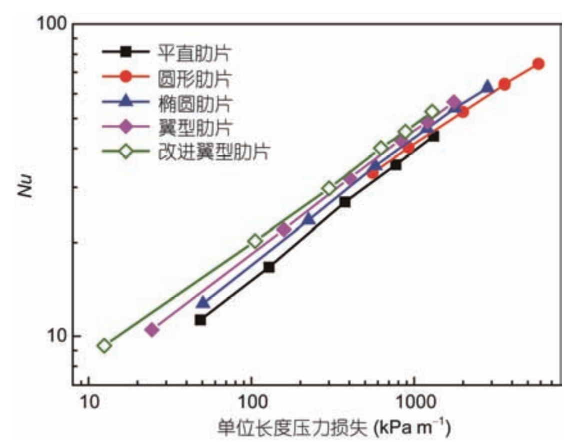

图 13 (网络版彩色)综合换热性能对比

Figure 13 (Color online) Comparision of comprehensive heat transfer performance

在换热器评价中，综合性能的影响十分关键，如何平衡换热器传热与阻力的关系对于优化换热器结构非常重要. 图13对几种肋片结构印刷电路板换热器综合传热性能进行评价，以单位长度的泵功损耗为横坐标，以平均*Nu*数为纵坐标对比换热器的综合换热性能. 由图可知，在等泵功损耗的条件下，平直肋的传热性能最差，依次较优的是圆形肋、椭圆肋和翼型肋，改进的翼型肋结构印刷电路板换热器传热能力最强. 因此，改进的翼型肋结构可以有效提高印刷电路板换热器的综合传热性能，在高热流密度电子器件散热的具有很好的应用前景.

4 结论

本文从常用的连续平直肋印刷电路板换热器结构出发，在相等最小流通截面积条件下与非连续的圆形肋印刷电路板换热器进行了性能对比，接着在等周长条件与椭圆肋、翼型肋和改进的翼型肋印刷电路板换热器进行了性能对比. 发现非连续肋结构可以更强烈地扰动流体，比连续平直肋结构具有更强的换热能力，在等流量条件下散热表面温度更低；与平直肋结构比较，相同周长的圆形肋、椭圆肋、翼型肋和改进翼型结构的传热性能分别提升了70.1%, 45.5%, 29.1%和20.2%，而阻力增加了340%, 114%, 40.9%和5.6%，改进的翼型肋结构在等泵功条件下换热性能最强.

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Summary for "不同肋片结构的印刷电路板换热器传热与阻力特性"

Heat transfer and pressure drop performance of printed circuit heat exchanger with different fin structures

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With the development of compact electronic system, the cooling problem with high heat flux in the electronic system has attached much more attention. The high-efficiency cooling devices with micro-channels are investigated and widely used in order to stabilize the surface of the component under the safe temperature. In recent years, a new type of cooler called printed circuit heat exchanger (PCHE), which has characteristics of high heat transfer ability and high compactness, is applied to act the heat sink of devices with high heat flux. The plates of the PCHE are fabricated by photochemical etching method, which can easily process the complex flow channels at low cost. Then, the plates can be stacked and brazed with the diffusion bonding technique in the vacuum circumstance. In this paper, the electronic device with the heat flux of 6.05×105 W/m^2 is cooling by water at 25°C and 0.2 MPa. The geometric dimension is 143.2 mm×30 mm and the material is copper. Meanwhile, the heat is original generated from the bottom of the device and the PCHE is fixed on the top of the model to transfer heat. The hydrodynamic and heat transfer performances of PCHEs with different structures of fins are analyzed by numerical method. The models of PCHE with continuous straight fins and discontinuous fins, including the circle fins, ellipse fins, airfoil fins and modified airfoil fins, are constructed. It is worth to point out that the straight model and the circle model are compared in the same cross section area and the other three discontinuous models are compared in the same fin perimeters. Furthermore, the symmetry boundary condition is used in the width direction and the edge effect is neglected according to previous research. The SST k-ω turbulence model assembled in the commercial CFX 12.1 software is validated reasonably to solve the problem in our cases. The result shows that the discontinuous circle fins have better heat transfer performance than the continuous straight fins, which because the fluid can break the boundary layer more effectively with the velocity variation in flow direction. However, the pressure drop also increases in the discontinuous model due to the separated blocks. On the other hand, it can be seen that the Nusselt number increases with the increase of Reynolds number and the gradient become slow, which indicated that it is limited to enhance the heat transfer by increasing the mass flow rate. However, the pressure drop increase exponentially at high Reynolds number. The average Nusselt number of the PCHE with circle fins, ellipse fins, airfoil fins increases 70.2%, 45.5% and 29.1% and the pressure drop also increases 340%, 114% and 40.9%, respectively, comparing with the continuous straight fins. Furthermore, it is found that the PCHE cooler with modified airfoil fins has better comprehensive heat transfer performance, which is based on the heat transfer rate and pressure loss per unit length, especially under the high mass flow rate condition. Comparing with the continuous straight fins, it can be seen that the average Nusselt number increases by 20.2%, and the pump power only increase by 5.6%. It can be concluded that the reduction of pressure loss is the major point for the optimization of the PCHE with discontinuous fins.

electronic cooling, printed circuit heat exchanger, modified airfoil fin, comprehensive heat transfer performance

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