

铜基超疏水表面改性强化冷凝传热

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摘要: **目的** 提高超疏水铜管的传热系数, 产生并长久维持珠状凝结, 在冷凝过程中实现从膜状冷凝到珠状冷凝的转变。**方法** 首先以硬脂酸铜和环氧树脂为原料, 设计并制备超疏水材料, 通过静电喷涂法在铜基换热器表面制备超疏水涂层, 通过喷枪将配制好的硬脂酸铜悬浮液加压, 将所制备的硬脂酸铜悬浮液通过喷枪的作用分散为微米级以及纳米级的小颗粒, 然后将这些小颗粒叠加涂覆到铜基底上, 最终会形成具有微纳米级复合阶层粗糙结构的均匀涂层。在此基础上, 搭建冷凝传热试验系统, 探究水蒸气在超疏水表面冷凝传热性能。**结果** 试验发现, 在静电电压 90 kV 的条件下, 所制备的超疏水材料和热固性粉末比例为 1 : 5 时性能最好, 接触角达到 154.3°, 涂层机械稳定性最佳。经喷涂处理后的换热器在高温水蒸气气流下仍保持超疏水性, 且在冷凝传热试验中, 超疏水铜基换热器放热量以及传热系数大大增加, 放热量比常规盘管提高 23.6%, 而传热系数也比常规盘管提高 38%。**结论** 通过静电喷涂法可制备出超疏水材料, 且其机械稳定性较好。超疏水膜层能够有效实现液滴跳跃和自去除, 在高温气流中保持超疏水性。在稳定的蒸汽流下, 超疏水换热器的放热量以及传热系数比常规换热器有了较大提高。

关键词: 超疏水涂层; 接触角; 膜状凝结; 珠状凝结; 传热系数

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Condensation Heat Transfer Enhancement by Copper-based Superhydrophobic Surface Modification

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ABSTRACT: Hydrophobic copper stearate powder was prepared by the reaction of anhydrous copper sulfate with sodium stearate. It was mixed with epoxy resin in the ratio of 5 : 1 by mass and coated on the copper sheet uniformly by electrostatic spraying. The powder was cured in an oven at 80 °C for 12 h and then removed. The light blue copper stearate powder evenly covered the copper-based surface, and the film was stable and unlikely to peel off. The surface water droplets appeared as full spheres and did not appear to be spreading. SEM images and the microscopic morphology showed scale-shaped and staggered stacking arrangement, forming a micro- and nano-graded structure. Its static contact angle reached 154.3°, and the superhydrophobic film layer was successfully constructed on the copper surface. The same process conditions were used to construct a superhydrophobic film on the coil heat exchanger surface to realize the transformation of its surface filmwise condensation to dropwise condensation and to strengthen the heat and moisture transfer during water vapor condensation. The

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steam generation system was used to provide constant steam to the coil heat exchanger without interruption, as well as to enable high-precision temperature and flow measurement.

When water vapor came into contact with the wall of the copper tube below its saturation temperature, the condensate quickly spread into a liquid film and adhered to the wall. It continuously accumulated until gravity was greater than the viscous force and slowly slides off from the wall. When the surface of the heat exchanger coil was transformed into a superhydrophobic state, the condensate could not wet the wall surface well and formed multiple small droplets and then dripped down rapidly, which could effectively achieve droplet jumping and self-removal. The heat transfer performance of the tube was studied in convective heat transfer experiments. Due to the good balance between droplet nucleation and separation, the heat transfer coefficient of the superhydrophobic tube was increased by 38% compared with that of the copper tube. The superhydrophobic film did not peel off or lose the superhydrophobic performance when the high temperature air flowed through. The variation of temperature and humidity of water vapor inlet and outlet and the variation of water temperature in the condenser inlet and outlet was recorded.

Dropwise condensation was difficult to produce and maintain for a long time on conventional metals. The hydrophobic coating was prepared by electrostatic spraying on the copper-based heat exchanger surface to realize the transformation from filmwise condensation to dropwise condensation during the condensation. The prepared hydrophobic material and thermosetting powder with a ratio of 5 : 1 showed the best stability performance with a contact angle of 154.3° and the best coating performance. The gas condensation experiments on the heat exchanger surface showed that the superhydrophobic filmwise could effectively achieve droplet jumping and self-removal, and the high temperature airflow did not cause the superhydrophobic filmwise to peel off or lose its superhydrophobic performance, and the heat transfer coefficient was 38% higher than that of conventional coils.

KEY WORDS: superhydrophobic coating; contact angle; filmwise condensation; dropwise condensation; heat transfer coefficient

超疏水表面具有防结冰^[1-2]、防腐和自清洁^[3-4]以及降低流动阻力^[5]等优点。目前, 常用化学方法^[6]、水热方法^[7]和电沉积^[8-10]等方法来制备超疏水表面。但是现有的方法和路径所制备的超疏水材料大多数仍然存在机械耐久性和化学稳定性较差的问题, 很大程度上制约了其在科学研究领域以及实践应用领域的发展。目前制备的超疏水表面在机械稳定性上都有待改善, 特别对于沉积^[16-17]、纺丝等方法得到的结构, 容易受到外力的破坏^[15], 还不能承担覆冰所造成的机械强度。有些超疏水材料在使用寿命上有待进一步发展, 在日晒雨淋后, 超疏水表面的蜡状物质会脱落, 进而使超疏水性能降低, 以致消失。目前制备超疏水材料的方法多种多样, 但大多数比较复杂, 并且操作起来有一定的难度, 不宜大规模、大范围的使用。现在还有一部分超疏水制备方法所消耗的成本比较高, 对于所要引进材料的地区和企业收益存在很大的限制^[18-20], 这也制约了超疏水材料的发展前景。

静电喷涂方法^[11-12]与这些方法相比。静电喷涂法就是将所制备的试剂通过喷枪的作用分散为微米级以及纳米级的小颗粒, 然后将这些小颗粒叠加涂覆到基底上, 最终会形成具有微纳米级复合阶层粗糙结构的均匀涂层。此方法具有设备成本低、工艺简单、可控性高等优点^[13]。

硬脂酸铜为非极性分子, 其本身就具有疏水性, 属于低表面能物质。通过喷枪将配制好的硬脂酸铜悬

浮液加压, 增压后硬脂酸铜悬浮液分散为微纳米级的颗粒, 通过喷枪喷嘴以雾化的形式喷涂出去并将其叠加覆盖在基底上形成均匀涂层。因此, 采用静电喷涂法可方便地制备出具有超疏水性能的表面。此外, 通过喷涂法制得的涂层不仅具备良好的再生性能, 而且方法简单易操作, 所以受到了很多研究者的青睐。将制备好的试剂搅拌均匀后通过喷枪口喷出, 因为会出现前后压差的骤然变化, 所以喷涂试剂会在空中通过流体表面本身收缩张力的作用形成微纳米级的分散小颗粒, 这些分散的小颗粒连绵不断地附着在基底表面, 最终经干燥得到具有不同粗糙结构的涂层。

目前, 超疏水线圈是用湿化学蚀刻法成功制备的^[20-22]。然而, 其制备过程复杂, 时间较长, 无法实现大规模生产。更糟糕的是, 通过溶液蚀刻形成的超疏水结构是易损坏的, 其耐久性较差^[23]。因此, 将自身制备的超疏水材料通过静电喷涂法喷涂到铜线圈换热器上, 通过观察水蒸气在其表面形态, 发现无论是珠状凝结还是膜状凝结, 凝结液都是构成蒸汽与壁面交换热量的热阻载体。膜状凝结形成连续液膜覆盖冷凝壁面, 凝结放出的相变潜热必须穿过液膜才能传到冷却壁面。在减小热阻方面, 珠状凝结相比于膜状凝结具有很大的优越性。因此研究者一直致力于如何将工程技术常用的材料经过表面改性使之成为疏水乃至超疏水表面, 从而产生并长久维持珠状凝结^[24-25]。

1 试验

1.1 材料和试剂

试验过程中所用的是一般的铜盘管换热器(圣火不锈钢制品厂, $\phi 8\text{ mm} \times (1 \sim 2)\text{ mm}$)。一系列的化学药品包括硬脂酸钠(天津致远化学试剂有限公司, 99%)、

硫酸铜(天津市恒兴化学试剂制造有限公司, $\geq 99.0\%$)、环氧聚酯型粉末涂料(中国云南浩岑机械设备有限公司)。整个试验过程中所用的水均为去离子水。

1.2 铜基超疏水膜层的制备

图 1 显示了铜基超疏水膜层的制备过程, 具体包括以下步骤。

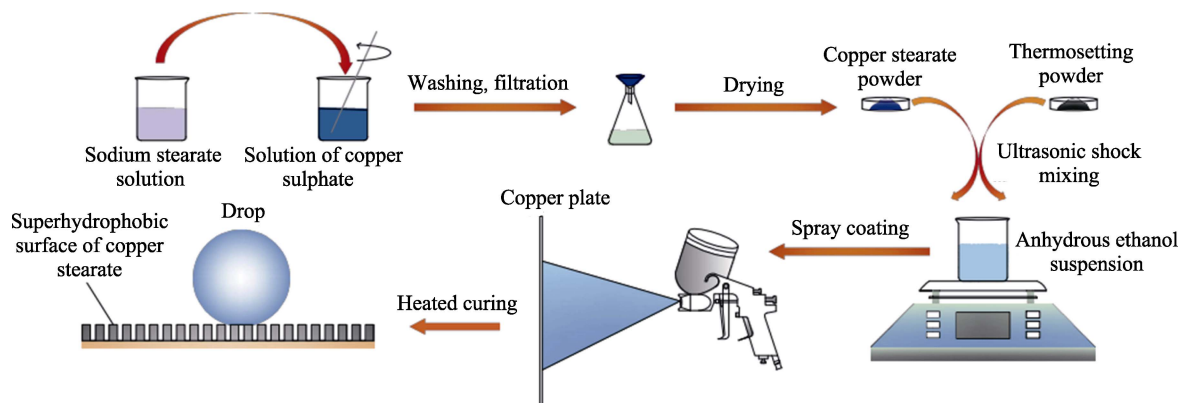


图 1 铜基超疏水膜层的制备过程

Fig.1 Preparation process of copper-based superhydrophobic film

1.2.1 超疏水材料的制备

称取 10 g 硬脂酸钠于 200 mL 去离子水中, 加热溶解后, 配成澄清溶液。称取 15 g 无水硫酸铜 ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) 溶解到 600 mL 去离子水中。硬脂酸钠溶液中置于 70 °C 的磁力搅拌器中, 再将无水硫酸铜溶液滴加其中, 边滴加边搅拌, 确保溶液中离子反应完全。磁力搅拌器搅拌 15 min, 得到硬脂酸铜悬浮液。再将硬脂酸铜悬浮液多次过滤, 过滤过程中用热水冲洗, 除去表面大部分白色物质, 过滤后将其放置于 80 °C 的烘箱中烘干水分离备用。

1.2.2 铜基预处理

由于所要涂装的零件是铜制换热器, 其参数见表 1。为了清除其上的灰尘、油污、金属氧化物等瑕疵, 同时也为了提高铜基与粉末的结合力, 所以要对铜基

进行预处理。铜基预处理质量不好容易造成涂膜脱落、缩孔等问题。

具体处理过程如下: 先用磨砂纸对铜基进行处理, 接下来用 0.1 mol/L 氢氧化钠溶液 (NaOH) 在 60~80 °C 条件下对其进行化学除油, 时间持续 7~8 min; 然后用 60~70 °C 的热水对其进行流动清洗, 时间持续 1~2 min; 接着用冷水冲洗 1~2 min; 之后用 0.1 mol/L 氢氧化钠溶液 (NaOH) 对其进行碱腐蚀, 在 60~80 °C 温度下持续 5~15 min; 再用流动热水和冷水冲洗 (条件同上); 然后用 0.1 mol/L 的草酸溶液 ($\text{C}_2\text{H}_2\text{O}_4$) 进行化学抛光, 在室温下持续 10~20 s; 再用流动热水和冷水冲洗 (条件同上); 最后将其放置在 60 °C 的烘箱中烘干即可。预处理后的铜基换热器如图 2 所示。利用磨砂纸、酸洗和碱洗将铜基表面氧化层和污垢等物质去除, 再进行试验。

表 1 铜基换热器相关参数

Tab.1 Copper-based heat exchanger's related parameters

Heat exchanger's related parameters	Numerical value
Thermal conductivity of disk copper tube heat exchanger $\lambda/(\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1})$	386
Coil outer diameter d/m	0.014
Coil wall thickness δ/m	0.002
Heat transfer area (outer surface area of the coil) A_0/m^2	0.87
Unit inner surface area of tube (inner surface area of coil) A_i/m^2	0.74
Single tube length l/m	17.5

1.2.3 静电喷涂

将制备好的疏水材料倒入静电喷涂机的下方杯桶内, 打开空气压缩机, 超疏水材料由于压力作用从喷枪中喷出。静电喷涂机使超疏水材料携带负电荷, 而铜基换热器携带正电荷, 从而使疏水材料吸附在金属表面, 完成喷涂。喷涂完成后为材料的固化阶段, 将其放置在电热鼓风干燥箱中, 在 80 ℃ 的条件下进行 12 h 左右。等待铜基换热器冷却后进行厚度和质量的测量, 并观察超疏水材料的粘合效果。表 2 为静电喷涂所用仪器和材料的详细信息。表 3 为喷涂条件参数。喷涂固化后的铜基换热器如图 3 所示。



图 2 预处理后的铜基换热器
Fig.2 Pretreated copper-based heat exchanger

表 2 静电喷涂所用仪器和材料详细信息
Tab.2 Details of equipment and materials used in electrostatic spraying

Name of instrument and material	Manufacturer
Electrostatic spraying machine (COLO-900T)	Hangzhou Carover Spraying Equipment Co., Ltd.
Electric blast drying box (110-00A)	Jinan Olebo Scientific Instrument Co., Ltd.
Electronic balance (JE-502)	Shanghai Puchun Metering Instrument Co., Ltd.
Epoxy polyester type powder coating	Yunnan Haoling Machinery Co., Ltd., China
Dispersing machine (FS100-S)	Shanghai Lichen Bangxi Instrument Technology Co., Ltd.

表 3 喷涂条件参数
Tab.3 Spraying condition parameters

Spray conditions	Baseline value	Parameter change
Electrostatic pressure	90 kV	60-100 kV
Powder output	6 m ³ /h	2-8 m ³ /h
Curing temperature	80 ℃	70-90 ℃
Curing time	12 h	10-14 h



图 3 喷涂固化后的铜基换热器
Fig.3 Spray-cured copper-based heat exchanger

1.2.4 超疏水铜基表面表征

使用接触角仪 (OCA 25, 德国奥得利诺) 分析液滴在制备的铜基表面上的湿润性, 将多次测量的平均值作为接触角。通过扫描电子显微镜 (MIRA LMS, 捷克 TESCAN) 观察薄膜的表面形态。

1.2.5 铜基超疏水机械稳定性测试

在日常生活中, 超疏水材料难免会有磨损的情

况。因此, 对铜基表面的超疏水进行稳定性测试。为了探究静电喷涂得到的超疏水铜基在经过不同程度的磨损后的超疏水性能。本试验将制备好的超疏水铜片 (此时采用最佳比例硬脂酸铜: 环氧树脂=1:5) 贴附在 100 g 的砝码底部, 然后将其放在型号为 1500# 的砂纸上推动, 记录随摩擦距离增加后超疏水涂层接触角以及滚动角的变化。试验如图 4 所示。

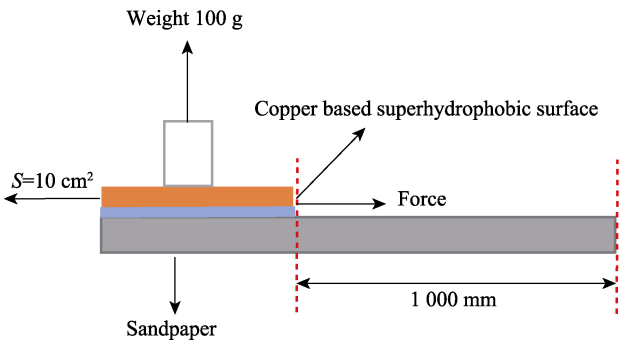


图 4 超疏水涂层机械稳定性试验方法示意图
Fig.4 Schematic diagram of test method for mechanical stability of superhydrophobic coatings

1.3 冷凝传热 (CHT) 试验

1.3.1 冷凝传热系统搭建

该系统由温度传感器 (MIK-WZPK, 杭州美控自动化技术有限公司)、微型电磁泵 (KP1, 东莞市伽伦电子有限公司)、无纸记录仪 (MIK-R6000C, 杭州米科传感科技有限公司)、蒸汽发生系统、水泵、压力计、阀门、水箱以及一些连接管道等部件组成。首

先在蒸汽发生系统两端分别连接一个微型电磁泵和压力表,铜基换热器放置在蒸汽发生系统的蒸汽出口上方,其周围放置一个亚克力板,铜基换热器的进出

口两端各自连接一个温度传感器,进出口的通道上安装一个水泵以便实现冷却水的循环。系统原理图、实物图分别如图 5a—b 所示。

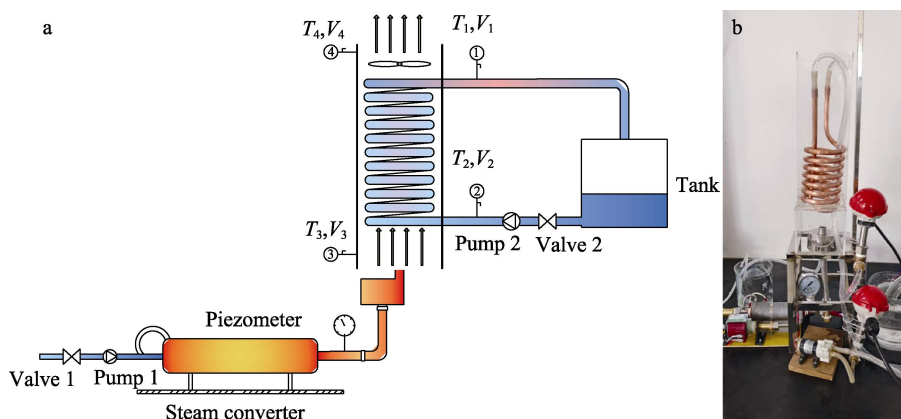


图 5 冷凝传热系统原理图、实物图

Fig.5 System schematic diagram and physical diagram of condensation heat transfer system

1.3.2 冷凝传热试验过程

连接好各部分必需的部件和设备,实物图如图 5b 所示。首先对没有喷涂超疏水材料的换热器进行试验。阀门 1 和水泵 1 分别负责蒸汽发生系统中水的开关和供给。蒸汽发生系统的右端安装一个压力计,实时监测管内压力变化,以防事故的发生;阀门 2 和水泵 2 负责铜基换热器中冷却水的循环和供给;铜基换热器周围放置罩子以防蒸汽散失。打开阀门 1 和水泵 1、阀门 2 和水泵 2,蒸汽由出口向上排出,换热器内冷水循环流动。由于罩子的存在,蒸汽与铜基换热器充分接触,蒸汽在换热器表面实现换热;温度传感器分别记录换热器进出口两端的温度值。试验结束后通过无纸记录仪拷贝出数据进行分析。

对铜基换热器表面进行简单清洗并烘干后,在换热器表面用静电喷涂法构建超疏水膜层,用制备的超疏水材料和热固性粉末以最佳比例混合进行测试。具体试验过程同上。

2 结果和讨论

2.1 超疏水材料表面湿润特性

当蒸汽在饱和温度以下接触管壁时,有两种不同的冷凝形式。当冷凝液不能很好地润湿壁面时,冷凝液会在壁面上形成小液珠,称为珠状凝结。根据液体与壁面接触角 θ 的大小把固体表面分为亲水表面 ($\theta < 90^\circ$) 与疏水表面 ($\theta > 90^\circ$),其中大于等于 150° 的表面成为超疏水表面。表面的亲、疏水特性对其上发生的蒸汽凝结有很重要的影响^[30]。接触角是表征固体表面润湿性的一个重要指标,是指固液结合线与穿过气、液、固相交点的气液界面切线之间的角度^[26-29]。

在本次试验中,研究了利用静电喷涂法喷涂不同

混合比例 (1:3、1:4、1:5、1:6) 的超疏水材料和热固性粉末对铜基换热器表面湿润性的影响,所得结果如图 6 所示。超疏水表面接触角随混合比例先增大后减小,而滚动角随混合比例先减小后增大。这是因为选用的固化剂环氧树脂是一种常用的低表面能改性剂^[34],添加恰当时,可适当增强材料表面的超疏水性。因此,当硬脂酸铜和环氧树脂混合比例为 1:5 时获得最佳接触角,铜基换热器表面与水滴的接触角为 154.3° ,滚动角为 3° 。

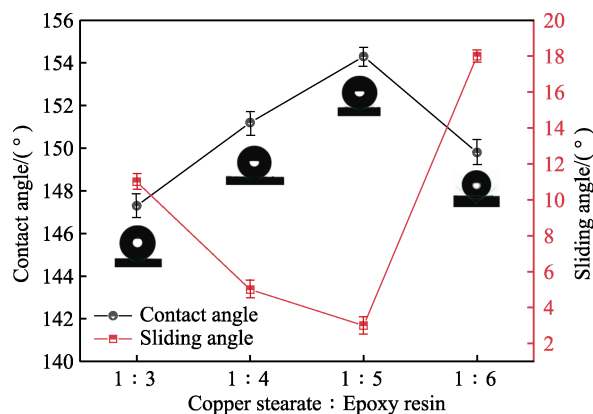


图 6 硬脂酸铜和环氧树脂的比例分别为 1:3、1:4、1:5、1:6 时的接触角和滚动角

Fig.6 Contact angle and sliding angle when the ratio of copper stearate to epoxy resin is 1:3, 1:4, 1:5, 1:6, respectively

2.2 超疏水材料机械稳定性

摩擦试验初始时,样本接触角为 154.3° ,滚动角为 3° ,具有较好的超疏水性能。如图 7 所示,在超疏水铜片进行摩擦,到 100 mm 后,其接触角略有下降,滚动角略有升高,但依然呈现出超疏水性能;当摩擦

到 200 mm 时, 其接触角依旧大于 150° , 但此时滚动角已然增大且大于 10° ; 超疏水铜片的滚动角也从初始的 3° 增大到 65° 。这说明铜片的超疏水表面从初始的低黏附性转变为高黏附性。在摩擦到 600 mm 时, 此时铜片表面接触角为 149.1° , 根据定义, 此时样品表面由超疏水表面变为疏水表面。最后到达 1 000 mm 时, 接触角最低降到 142.8° , 仍表现出疏水性能。在经过摩擦试验后, 证明通过静电喷涂法喷涂的超疏水材料具有很好的机械稳定性。

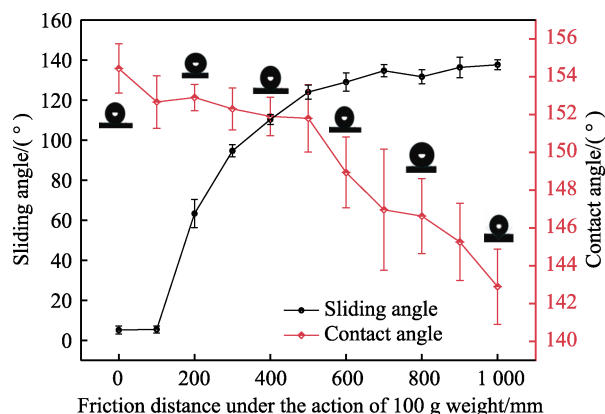


图 7 超疏水铜片表面接触角与滚动角随滑动距离变化示意图

Fig.7 Schematic diagram of surface contact angle and sliding angle of superhydrophobic copper sheet as a function of sliding distance

2.3 超疏水铜基表面形貌

当制备的超疏水材料和热固性粉末混合比例为 1 : 5 时, 在铜基换热器表面形成了均匀的、致密的

涂层。图 8 为超疏水涂层断面 SEM 图。可以看出, 超疏水材料和环氧树脂形成的涂层厚度为 1.084 mm。

如图 9a—c 显示的是不同放大倍数下的超疏水铜基表面, 而图 9a'—c' 表示的是只喷涂了环氧树脂的铜基表面 SEM 图。可以发现, 环氧树脂表面较为稀疏, 而在加入超疏水材料后, 铜基表面形成了一种更致密、更均匀的微米薄膜结构, 通过图 9b 和图 9b' 的对比, 可以发现硬脂酸铜分子填补了环氧树脂分子之间的空隙, 形成一种网状结构。通过图 9c 和图 9c' 的对比, 还可以看出一部分硬脂酸铜分子同时在环氧树脂分子表面, 使原本光滑的环氧树脂分子表面变得粗糙, 从而导致膜层粗糙度变大。表面形态和纹理对于超疏水表面的形成起到了很大的作用^[32]。微纳米结构的存在导致空气被困在团簇之间的间隙, 这些被困的空穴不允许粗糙的表面被液体湿润, 减小液滴与铜基的接触面积, 降低黏性阻力, 使液滴更容易脱落, 使铜基表面呈现超疏水性^[33]。

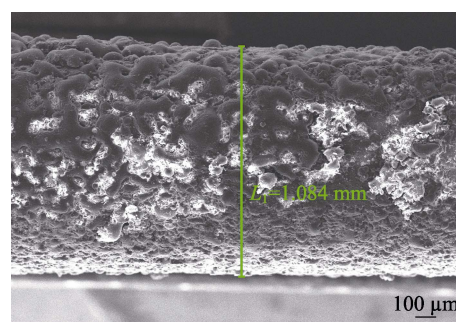


图 8 超疏水涂层的断面 SEM 图
Fig.8 Cross-sectional SEM image of superhydrophobic coating

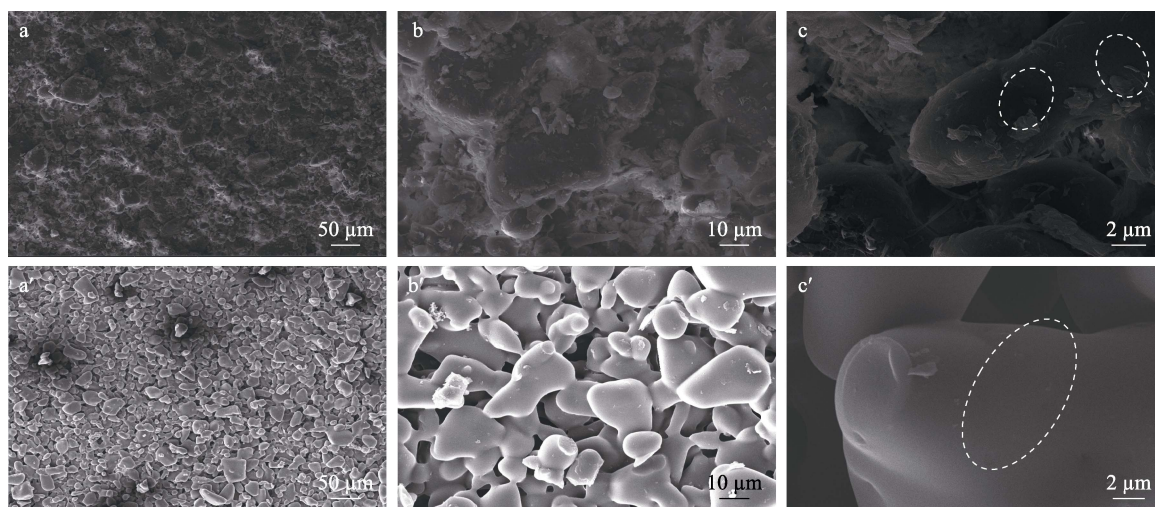


图 9 喷涂 1 : 5 硬脂酸铜与环氧树脂混合比例后不同放大倍数的铜基表面 SEM 图 (a—b), 喷涂环氧树脂后不同放大倍数的铜基表面 SEM 图 (a'—c')

Fig.9 SEM images of copper-based surface at different magnifications after spraying with a mixing ratio of 1 : 5 copper stearate and epoxy resin (a), (b), (c), SEM images of copper-based surface at different magnifications after spraying epoxy resin (a'), (b'), (c')

2.4 超疏水铜基换热器传热强化研究

2.4.1 冷凝传热试验计算

在盘管换热器表面构建超疏水膜层, 实现其表面膜状凝结向珠状凝结的转变, 强化水蒸气凝结过程中的热湿传递。蒸汽发生系统用于不间断地向盘管换热器提供恒定蒸汽, 以及能够进行高精度的温度和流量测量。保持管内平均水温 40 °C 为定性温度, 管内热水流速为 0.5 m/s, 从而保持在相同时间内水流量相同, 冷凝过程中, 铜管换热器放热量以及总传热系数可通过式 (1) — (5) 计算。

铜管换热器换热量:

$$Q = C_p \cdot m \cdot \Delta t \quad (1)$$

管内对流换热系数计算:

$$h_i = 0.023 \frac{\lambda_f}{d_i} Re^{0.8} Pr^{0.4} \quad (2)$$

以盘式铜管换热器外表面积 A_0 为基准的传热系数 K 的热阻方程式:

$$K = \frac{1}{\frac{1}{h_o} + \frac{1}{h_i} \left(\frac{A_0}{A_i} \right) + R_0 + R_i \left(\frac{A_0}{A_i} \right) + \frac{\delta A_0}{\lambda A_m}} \quad (3)$$

可得到铜管外侧对流换热系数 h_o :

$$h_o = \frac{1}{\frac{1}{K} - \frac{\delta A_0}{\lambda A_m} - \left(\frac{1}{h_i} + R_i \right) \frac{A_0}{A_i} - R_0} \quad (4)$$

此时管外对流换热系数拟合方程式:

$$Nu = C Re^n Pr^m \quad (5)$$

式中: u 为水流流速, m/s; Pr 为普朗特数 (与温度相关); ν 为运动黏度, m^2/s ; d_o 、 d_i 分别为盘管内外径, m; C_p 为水的比定压比热容, $J/(kg \cdot K)$; m 为盘管内水的质量, kg; Δt 为铜管换热器进出口温度

差值, K; h_i 、 h_o 分别为盘管内外侧传热系数, $W/(m^2 \cdot K)$; R_i 、 R_o 分别为盘管内外侧涂层热阻, $(m^2 \cdot K)/W$; A_i 为盘管平均换热面积, m^2 ; A_m 、 A_0 分别为管子内外传热面积, m^2 ; δ 为铜管管壁厚度, m; λ 为铜管热导率, $W/(m^2 \cdot K)$; λ_f 为铜管内流体热导率, $W/(m^2 \cdot K)$ 。此时努塞尔数 $Nu = h_o \cdot d_o / \lambda_f$, 雷诺数 $Re = u \cdot d_o / \nu$ 。

2.4.2 冷凝传热试验可靠性验证

首先用经预处理的铜基换热器进行膜状冷凝试验从而确定系统的可行性和有效性。如图 10 所示的经预处理的铜基换热器冷凝换热试验值和 Nusselt 膜状凝结理论曲线图的对比, 本系统试验值与理论值偏差在 25% 以内, 可认为系统参数测量及数据计算是具有可信性的。

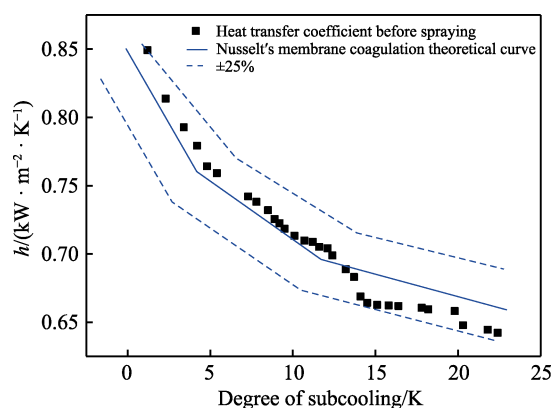


图 10 膜状冷凝试验值与 Nusselt 理论值比较
Fig.10 Comparison of experimental values of film condensation with Nusselt's theoretical values

2.4.3 冷凝传热试验相关结果

图 11a 为小过冷度光滑铜基表面冷凝液滴的图像, 由图可看出, 铜基表面上的液滴没有成球形, 水

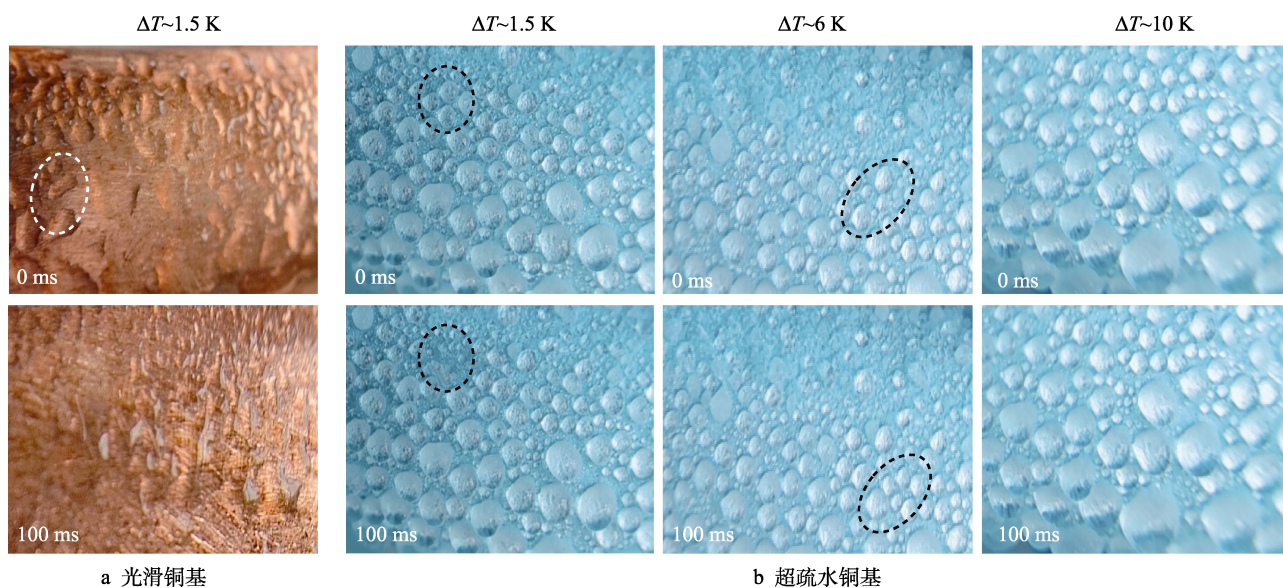


图 11 光滑铜基和超疏水铜基表面不同过冷度条件下的冷凝液滴图像
Fig.11 Condensation droplet images on smooth copper-based and superhydrophobic copper-based surfaces under different subcooling conditions

滴呈膜状凝结。图 11b 为超疏水铜基表面在不同过冷度的条件下冷凝液滴的图像, 由图可看出, 在超疏水表面一部分液滴可以快速地表面滑落, 有效实现液滴跳跃和自去除, 让表面裸露出来进行换热, 而且也有部分水滴快速生长, 其更新频率较快。从过小过冷度到大过冷度, 可以明显看出冷凝液滴的尺寸变大, 冷凝液滴的黏滞力增大, 使液滴难以在重力条件下从超疏水表面脱落, 最终降低了液滴的更新速度, 大大影响了冷凝传热效果, 降低传热性能。

图 12 表示了喷涂超疏水材料前后铜基换热器表面的换热系数随过冷度的变化。由图 12 可看出, 随后过冷度增大, 喷涂前后的换热器换热系数均呈曲线下降趋势, 并且喷涂后的铜基换热器传热系数比喷涂前铜基换热器的传热系数明显增大。根据 3 次试验得出的平均值, 喷涂前传热系数为 $0.758 \text{ kW}/(\text{m}^2 \cdot \text{K})$, 而喷涂后的传热系数为 $1.046 \text{ kW}/(\text{m}^2 \cdot \text{K})$, 相较于喷涂前铜管的传热系数提高了 38%。

如图 13 所示, 喷涂后的铜基换热器比喷涂前铜基换热器的放热量明显增大。根据 3 次试验得出的平均值, 喷涂前放热量为 39.7 kW , 而喷涂后的放热量为 49.07 kW , 相较于喷涂前铜基换热器的放热量提

高了 23.6%。根据放热量和传热系数数据显示, 超疏水材料喷涂后大大提高了换热器的传热性能。

3 结论

采用静电喷涂法在铜基换热器表面制备超疏水膜。研究了不同超疏水材料和热固性粉末的混合比例对超疏水膜性能的影响。当比例从 1:3 增加到 1:6 时, 超疏水表面的静态接触角先增大后减小。当混合比例为 1:5 时, 铜基表面形成了超疏水结构, 静态接触角为 153.4° , 滚动角为 3° , 其超疏水性能以及机械稳定性最佳。在稳定的蒸汽流下, 超疏水换热器的放热量比常规换热器高 23.6%, 其传热系数比常规换热器高 38%。

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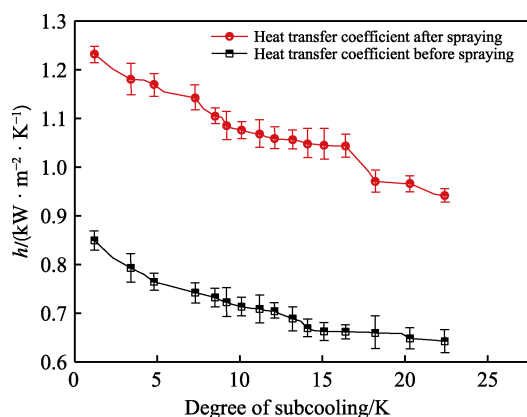


图 12 喷涂前后铜管传热系数变化

Fig.12 Change of heat transfer coefficient of copper tube before and after spraying

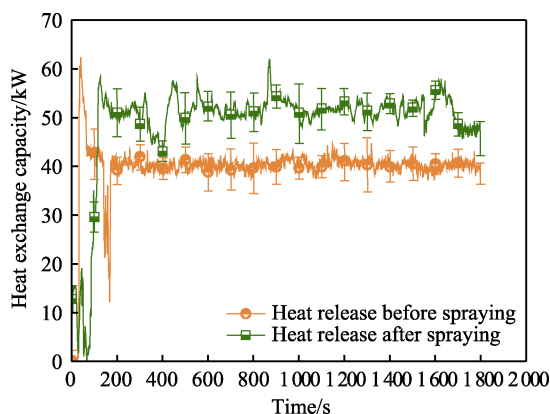


图 13 喷涂前后铜管换热器热流量变化

Fig.13 Change in heat release of copper tube before and after spraying

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