倾斜超疏水管外滴状冷凝液滴特性的可视化

马学虎*, 罗莎, 杜宾港, 吴羽隆, 兰忠, 郝婷婷, 刘旭, 王凯

大连理工大学化学工程研究所, 辽宁省化工资源清洁利用重点实验室, 大连 116024

* 联系人, E-mail: xuehuma@dlut.edu.cn

2016-06-14 收稿, 2016-07-16 修回, 2016-07-18 接受, 2016-09-21 网络版发表

国家自然科学基金重点项目(51236002)资助

摘要 含不凝气的混合蒸汽冷凝广泛存在于化工、石油、电力和海水淡化等领域. 在空气环境下超疏水表面具有较大的接触角, 有可能实现冷凝强化传热的目的. 但在纯蒸汽冷凝环境中, 液滴会完全润湿超疏水表面的微纳结构, 使表面的超疏水性“失效”. 而在含不凝气的混合蒸汽冷凝过程中, 若不凝气充满超疏水表面的微纳结构, 液滴呈Cassie或过渡态润湿模式, 保持或部分保持表面的超疏水特性. 对于倾斜表面, 冷凝液滴的脱落直径和冲刷周期都会发生变化, 进而影响冷凝传热. 因此, 深入认识混合蒸汽在不同倾斜角的超疏水竖管表面上的冷凝特性, 分析液滴的运动特性, 对探究冷凝机理和研发先进强化传热技术有重要意义. 本文利用氧化刻蚀-自组装的方法制备了紫铜管超疏水表面, 系统地研究了不同倾斜角度时混合蒸汽冷凝过程中液滴的接触角滞后、临界脱落直径以及冲刷周期, 并与纯蒸汽、疏水表面的情况进行了对比. 结果表明, 在铜管顶部(沿铜管圆周方向), 超疏水表面冷凝时接触角滞后小于疏水表面, 而在铜管中部和底部超疏水表面的接触角滞后则较大; 在超疏水表面条件下, 液滴的脱落直径随着倾斜角度的增加而增大; 冷凝液对超疏水表面的冲刷周期均大于疏水表面, 且随着倾斜角增加, 冲刷周期略有减小.

关键词 滴状冷凝, 超疏水表面, 不凝气, 倾斜角, 接触角滞后, 脱落直径, 冲刷周期

蒸汽相变传热在石油化工、制冷工业、航空航天等领域有广泛应用, 滴状冷凝由于其传热性能较膜状冷凝增大几倍到几十倍而受到众多研究者的关注^[1-3]. 通过调节管倾斜角度, 改变重力方向分力的大小, 探究不同重力场对冷凝传热的作用, 对探究滴状冷凝的传热控制机理和研发高效换热技术有重要意义.

滴状冷凝是一个伴随液滴核化、生长、合并和脱落的动态循环过程, 而液滴的形态、尺寸及动态特性受冷凝表面的物理化学结构^[4]、倾斜角度^[5]、界面特性^[6]等因素制约. 液滴动态特性如接触角滞后、脱落半径、冲刷周期等对蒸汽冷凝的传热性能影响显著. Sikarwar等人^[7]通过理论分析证实接触角滞后增加液

滴的临界脱落直径增大, 不利于传热. 冷凝液滴达到临界脱落直径会迅速脱落并冲刷表面, 促使冷凝表面更新循环, 加速冷凝过程的进程^[8,9]. Tanasawa等人^[10]从实验中证实液滴脱落直径增加会增加冲刷周期, 使冷凝传热效果显著下降, Le Fevre等人^[11-13]理论分析的结果与这一观点相吻合. Peng^[12]利用滴状冷凝传热模型, 定量分析得出了传热通量随脱落半径、接触角滞后的变化趋势, 表明随脱落半径和接触角滞后的增加, 传热通量快速下降且下降速度越来越慢. 同时, 模型分析也证明了冲刷周期的减小会加速表面更新, 强化冷凝传热.

当表面倾斜时, 液滴的接触角会在三相接触线处改变, 同时液滴发生形变, 影响冷凝传热的性能.

引用格式: 马学虎, 罗莎, 杜宾港, 等. 倾斜超疏水管外滴状冷凝液滴特性的可视化. 科学通报, 2017, 62: 1082-1089

Ma X H, Luo S, Du B G, et al. Visualization study on droplet dynamic characteristics in dropwise condensation on inclined super-hydrophobic tube (in Chinese). Chin Sci Bull, 2017, 62: 1082-1089, doi: 10.1360/N972016-00694

Caruso等人^[14]研究了混合蒸汽的冷凝传热性能,考虑不同的入口雷诺数和膜厚,当倾角 45° 时结果发生了明显变化. Sikarwar等人^[15]分析滴状冷凝的液滴尺寸与倾斜角度的关系,发现液滴平均尺寸随冷凝表面与水平面夹角的增加而减小. Chung等人^[16]在倾斜平板上下面进行纯蒸汽的滴状冷凝实验,结果显示,与水平面夹角大有利于传热,且上表面传热量高于下表面. Hosokawa等人^[17]研究了液滴脱落行为与传热系数之间的关系,并提出当倾斜管与水平夹角为 30° 时,传热系数最高. Ganzevles等人^[18]实验研究了冷凝器倾斜角度对气体-壁面传热热阻的影响,证明角度倾斜对传热有显著的强化作用. Bonner^[19]修正了滴状冷凝传热模型,分析得出水平表面的倾斜角越大,传热系数越高.

综上所述,对于倾斜管外蒸汽滴状冷凝传热强化,特别是水蒸气-不凝气混合蒸汽在超疏水表面上冷凝时液滴动态特性研究较少. 本文利用表面改性的方法,探究倾斜角度和不凝气对超疏水表面液滴动态特性的影响,并与纯蒸汽、疏水表面情况下进行对比,对蒸汽冷凝传热强化技术的研发提供指导.

1 实验系统及误差分析

倾斜管外蒸汽冷凝的实验装置如图1所示,主要包括4个部分,分别是冷凝室、蒸汽系统、冷却水系统和数据采集系统. 实验选用长度为430 mm的紫铜管(图1冷凝室内),其中有效传热部分长度为260 mm,管外径为20 mm,壁厚3 mm. 冷凝室与可调角度的圆盘相固定,可调节铜管的倾斜角度.

在实验过程的进行中,需要实时测定和采集冷却水进出口的温度、冷凝室内蒸汽的温度、锅炉内的温度及冷凝室内的压力. 实验系统所有对温度的测量均采用自制的T型铜-康铜热电偶测定,误差为 $\pm 0.05^{\circ}\text{C}$. 为了确保实验数据的稳定与准确性,冷却水进出口温度和冷凝室内蒸汽的温度都选用两根热电偶同时进行测定,并取其平均数进行计算. 冷凝室内蒸汽压力的测定选用日本Copal公司的PG-35 102R精密压力传感器,最大的误差为 $\pm 0.1\text{ kPa}$,具有较高的精度. 测量点如图1所示, T表示热电偶位置, P表示压力表位置. 此外,采用美国Photron公司Ultima APX-RS型号的高速摄像机观测管外冷凝时液滴动态特性进行可视化研究.

图1 (网络版彩色)实验装置流程图. 1, 锅炉; 2, 缓冲罐; 3, 气液分离器; 4, 冷凝室; 5, 倾角控制盘; 6, 计量罐; 7, 后冷器; 8, 凝液罐; 9, 11, 泵; 10, 冷水罐; 12, 流量计; 13, 混合器

Figure 1 (Color online) Schematic diagram of the experimental system. 1, Boiler; 2, buffer; 3, vapour, liquid separator; 4, condensation chamber; 5, tilt control panel; 6, measuring tube; 7, secondary condenser; 8, liquid tank; 9, 11, pump; 10, cooling water tank; 12, flow meter; 13, mixture

实验过程中直接测量参数和间接测量参数具有不确定度. 根据函数增量法, 利用误差传递原理计算出在不同条件下实验各间接物理量的不确定度: 温度为 0.05 K , 压力为 $\pm 0.1\text{ kPa}$, 热流量为 $\pm 11.90\%$, 表面过冷度为 $\pm 22.17\%$, 不凝气含量为 $\pm 1.91\%$.

2 实验结果与讨论

在紫铜管上利用十八烷基硫醇溶液自组装单层膜的方法制备疏水表面, 接触角为 148.7° ; 将打磨过的光滑紫铜管在氢氧化钾和过硫酸钾溶液中氧化刻蚀, 再利用十八烷基硫醇溶液自组装单层膜的方法制备超疏水表面的紫铜管, 接触角测定时, 液滴无法在新制得的超疏水表面停留, 迅速发生滚动脱落. 本文定义铜管倾斜方向与重力方向的夹角为 θ , 取竖直向下为正方向, 即竖直管的倾斜角度为 $\theta=0^\circ$, 另取 $\theta=30^\circ, 45^\circ, 60^\circ$ 三种不同的倾斜角度进行纯蒸汽及含不凝气蒸汽的冷凝实验, 如图2所示. 利用高速摄像对倾斜管圆周方向的顶部、中部、底部分别进行拍摄, 如图3所示.

2.1 冷凝液滴接触角滞后

(i) 混合蒸汽冷凝时液滴在竖直超疏水表面的接触角滞后. 如图4所示, 含10%不凝气的混合蒸汽在竖直超疏水管表面的接触角滞后为 4.7° , 纯蒸汽在竖直超疏水表面接触角滞后为 24.5° . 混合蒸汽冷凝

图2 (网络版彩色) 倾斜角度及液滴位置示意图

Figure 2 (Color online) Diagram of the inclined angle and location of the droplets

图3 (网络版彩色) 高速摄像拍摄角度示意图

Figure 3 (Color online) Diagram of screening direction by the CCD camera

时, 不凝性气体会聚集在超疏水表面的微纳结构中, 液滴与表面间形成Cassie或过渡态的润湿模式, 直接阻隔了固液相接触^[1], 黏滞力较小, 因此接触角滞后程度较小.

(ii) 混合蒸汽冷凝时液滴在倾斜超疏水表面的接触角滞后. 为了探究倾斜角度对接触角滞后的影响, 实验观察了含10%不凝气的混合蒸汽条件下, 不同倾斜角度超疏水铜管壁面处液滴的接触角滞后数值. 作为对照, 实验观察了混合蒸汽在疏水铜管、纯蒸汽在超疏水铜管、纯蒸汽在疏水铜管的冷凝实验, 同样测量了接触角滞后数据. 实验结果如图5所示.

对于超疏水管顶部的液滴, 由于受到了混合蒸汽中不凝气填充进微纳结构的影响, 其接触角滞后的程度会小于相同条件下疏水表面; 同时与超疏水表面在纯蒸汽条件下的接触角滞后相比, 也出现了下降, 但下降的幅度相对较小, 说明表面润湿性的差异对接触角滞后会产较为显著的影响.

对于超疏水管中部和底部的液滴, 在混合蒸汽与纯蒸汽两种条件下表现出了相类似的冷凝特性, 其接触角滞后较疏水表面相比, 均出现了较大幅度的增大, 而不凝气含量对其所造成的影响虽然存在, 但表现得并不明显, 同样可以得出表面润湿性的差异才是影响接触角滞后的决定性因素.

观察相同倾斜角度时不同位置液滴的接触角滞后, 由于不凝气和超疏水表面微纳结构的共同作用下, 液滴与表面间的黏滞力进一步减小, 而且顶部位置的液滴会受到管壁的支持力, 所形成的接触角滞后也相对较小. 对于铜管底部位置的液滴, 其重力所造成的影响更加显著, 相对而言形成了非常明显的接

图4 (网络版彩色)蒸汽在竖直超疏水管表面的接触角滞后. (a) 混合蒸汽; (b) 纯蒸汽

Figure 4 (Color online) Contact angle hysteresis on the vertical superhydrophobic tube with non-condensable gas (a) and without non-condensable gas (b)

图5 (网络版彩色)不同条件下铜管不同位置的接触角滞后. (a) 顶部; (b) 中部; (c) 底部

Figure 5 (Color online) Contact angle hysteresis on the different location of the inclined angle hydrophobic tube. (a) Top; (b) middle; (c) bottom

触角滞后.

2.2 冷凝液滴的脱落直径

图6为混合蒸汽在不同倾斜角度超疏水表面临界状态的冷凝液滴在正面拍摄的图像,相同的实验条件下选取处于临界状态的5个不同的液滴,测量并计算不同倾角下超疏水铜管表面的脱落直径,用下式计算:

$$D = \sqrt{ab}, \quad (1)$$

式中 a 和 b 分别为临界状态椭球形液滴长轴和短轴长度.

图6中依次排列出的是含10%不凝气的混合蒸汽,在倾斜角度为30°, 45°, 60°的超疏水表面临界状态的冷凝液滴,其每个可视化图像的比例尺单位长度均为5 mm. 运用Image Pro Plus软件测量并计算出液滴的长短轴和几何平均直径 D . 作为对照实验,用同样的方法实验观察了纯蒸汽条件下超疏水表面,混合蒸汽在疏水及超疏水表面冷凝的脱落直径,实验结果如图7所示. 从图7可以看出,在疏水和超疏水表面

图6 (网络版彩色)混合蒸汽在不同倾斜角度超疏水表面临界状态的冷凝液滴(10%不凝气). (a) 30°; (b) 45°; (c) 60°

Figure 6 (Color online) Condensing droplet on the super-hydrophobic surface at different inclined angles with 10% non-condensable gas. (a) 30°; (b) 45°; (c) 60°

上,不同倾斜角度时混合蒸汽冷凝的脱落直径均小于纯蒸汽冷凝.由于在不凝气存在的条件下,不凝性气体会在近壁面处形成气膜,影响固液接触^[1];特别是在超疏水表面上,不凝气充满微纳结构,壁面对液滴的黏滞力减小,使冷凝过程中合并的液滴在相对较小尺寸时便发生脱落.所以与在纯蒸汽条件下相比,管壁面处临界状态的脱落直径会出现减小的趋势.

从图7中还可以看出,冷凝时超疏水表面的脱落直径整体大于疏水表面.即使在含10%不凝气时,冷凝液仍然会浸入超疏水表面的微纳结构,形成了介于Wenzel和Cassie态的液滴下沉润湿模式^[20],相比无微纳结构的疏水表面,液滴与表面结构的黏滞力仍然较大,因此脱落直径增加.这一特征可从接触角滞

后的数值得以验证.

此外,超疏水表面上临界状态液滴的脱落直径随着倾斜角度的增大而增大,而疏水表面上临界状态液滴的脱落直径随着倾斜角度的增大而减小.分析由于随着铜管倾斜角度的不断增大,壁面对其所提供的支持力会随之增大,并且方向也会发生不断变化,从而改变了表面的润湿情况,进而改变了脱落直径.与兰忠^[21]提出的脱落模型值对比可知,在0°时与模型值相接近,当铜管倾斜时实验数值偏离模型计算值,一方面由于模型是基于竖直壁面建立的,在有倾斜角度时稍有偏差;另一方面再次证实了倾斜角度对脱落直径具有影响,这一特性可用于指导强化功能表面的蒸汽冷凝传热过程.

图7 (网络版彩色)混合蒸汽与纯蒸汽在不同倾斜角度疏水及超疏水表面的脱落直径

Figure 7 (Color online) Departure droplet size on the hydrophobic or super-hydrophobic surface at different inclined angles with and without non-condensable gas

2.3 冷凝液滴的冲刷周期

不同倾斜角度条件下液滴的冲刷周期如图8所示。在过冷度(蒸汽温度与表面温度差值)维持在一定区间的条件下,不凝气的存在使表面冲刷周期变长,表面更新频率减慢。在含10%不凝气的混合蒸汽条件下,随着倾斜角度的增加,凝液对超疏水表面的冲刷周期近似相同略有减小,不能认为其有明显的差别。可以得出,不凝气减慢了其表面冲刷周期,而倾斜角度对其的影响相对较小。

在混合蒸汽含量相同的条件下,将液滴对不同

润湿性表面的冲刷周期进行比较,不凝气对含微纳结构的超疏水表面会产生较大影响。因此对于同一倾斜角度,冷凝液对超疏水表面的更新速率最慢,表面冲刷周期最长。这是由于不凝气的存在,增加了气相热阻,减慢了液滴生长速率,因此导致冲刷周期增加。

3 结论

实验研究了纯蒸汽及含10%不凝气的混合蒸汽在不同倾斜角下超疏水及疏水表面的冷凝特性,结论如下:

(1) 对于超疏水管顶部的液滴,在混合蒸汽条件下,其接触角滞后的程度小于相同条件下疏水表面;同时与超疏水表面在纯蒸汽条件下的接触角滞后相比,也出现了下降,但下降幅度较小;对于超疏水管中部和底部的液滴,在混合蒸汽与纯蒸汽两种条件下表现出了相类似的冷凝特性,其接触角滞后较疏水表面相比,均出现了较大幅度的增大,说明表面润湿性的差异才是影响接触角滞后的决定性因素。

(2) 与纯蒸汽条件下相类似,含10%不凝气时液滴在疏水表面上的脱落直径随倾斜角度的增大而减小,在超疏水表面上其脱落直径随倾斜角度的增大而增大。

(3) 随倾斜角度的增加,冷凝液滴对表面的冲刷时间略有减小但并不明显,均小于竖直管表面的冲刷时间。

图8 (网络版彩色)不同倾斜角时铜管表面的冲刷周期。(a) 含10%不凝气蒸汽;(b) 纯蒸汽

Figure 8 (Color online) Sweeping cycle on the surface of different inclined angle tube. (a) 10% NCG; (b) pure steam

参考文献

- 1 Ma X H, Wang S F, Lan Z, et al. Wetting mode evolution of steam dropwise condensation on superhydrophobic surface in the presence of noncondensable gas. *J Heat Transfer*, 2012, 134: 021501
- 2 Collier J. *Convective Boiling and Condensation*. UK: McGraw-Hill, 1981
- 3 Rose J W. Dropwise condensation theory and experiments: A review. *Proc Inst Mech Eng*, 2002, 216: 115–128
- 4 Zhang B J, Cheng K, Kim K J, et al. Dropwise steam condensation on various hydrophobic surfaces: Polyphenylene sulfide (PPS), polytetrafluoroethylene (PTFE), and self-assembled micro/nano silver (SAMS). *Int J Heat Mass Transfer*, 2015, 89: 353–358
- 5 Sikarwar B S, Muralidhar K, Khandekar S. Effect of drop shape on heat transfer during dropwise condensation underneath inclined surfaces. *Int Phenom Heat Transfer*, 2013, 1: 339–356
- 6 Rausch M H, Leipertz A, Fröba A P. Dropwise condensation heat transfer on ion-implanted titanium surfaces. *Int J Heat Mass Transfer*, 2010, 53: 423–430
- 7 Sikarwar B S, Khandekar S, Muralidhar K. Dropwise condensation of metal vapors underneath inclined textured substrates. *Int Phenom Heat Transfer*, 2015, 3: 85–113
- 8 Grooten M H M, Van der Geld C W M. Dropwise condensation from flowing air-steam mixtures diffusion resistance assessed by controlled drainage. *Int J Heat Mass Transfer*, 2011, 54: 4507–4517
- 9 Izumi M, Kumagai S, Shimada R, et al. Heat transfer enhancement of dropwise condensation on a vertical surface with round shaped grooves. *Exp Therm Fluid Sci*, 2004, 28: 243–248
- 10 Tanasawa I, Ochiai J. Experimental study on dropwise condensation. *Bull Jpn Soc Mech Eng*, 1972, 16: 1184
- 11 Le Ferve E J, Rose J W. An experimental study of heat transfer by dropwise condensation. *Int J Heat Mass Transfer*, 1965, 8: 1117–1133
- 12 Peng B L. Steam condensation heat transfer enhancement and Lattice Boltzmann simulation for droplet dynamic behaviors (in Chinese). Dissertation for Doctoral Degree. Dalian: Dalian University of Technology, 2014 [彭本利. 液滴动态特性调控强化冷凝传热的研究和LB模拟. 博士学位论文. 大连: 大连理工大学, 2014]
- 13 Le Ferve E J, Rose J W. A theory of heat transfer by dropwise condensation. In: *Proceedings of 3rd International Heat Transfer Conference*. Chicago: American Institute of Chemical Engineers, 1966. 362–375
- 14 Caruso G, Maio D V. Heat and mass transfer analogy applied to condensation in the presence of noncondensable gases inside inclined tubes. *Int J Heat Mass Transfer*, 2014, 68: 401–414
- 15 Sikarwar B S, Muralidhar K, Khandekar S. Effect of drop shape on heat transfer during dropwise condensation underneath inclined surfaces. *Int Phenom Heat Transfer*, 2013, 1: 339–356
- 16 Chung B J, Min C K, Ahmadinejad M. Film-wise and drop-wise condensation of steam on short inclined plates. *J Mech Sci Tech*, 2008, 22: 127–133
- 17 Hosokawa T, Fujiwara Y, Ogami Y, et al. Heat transfer characteristic of dropwise condensation on an inclined circular tube. *Heat Recovery Syst CHP*, 1995, 15: 31–39
- 18 Ganzevles F L A, Van Der Geld C W M. The effect of the angle of inclination of a condenser on the gas-to-plate heat resistance in dropwise condensation. *Exp Therm Fluid Sci*, 2004, 28: 237–241
- 19 Bonner R W. Correlation for dropwise condensation heat transfer: Water, organic fluids, and inclination. *Int J Heat Mass Transfer*, 2013, 61: 245–253
- 20 Wang S F, Lan Z, Ma X H, et al. Dropwise condensation of steam and steam-air mixture on super-hydrophobic surfaces (in Chinese). *J Chem Ind Eng*, 2010, 61: 607–611 [王四芳, 兰忠, 马学虎, 等. 超疏水表面蒸汽及含不凝气蒸汽滴状冷凝传热实验分析. 化工学报, 2010, 61: 607–611]
- 21 Lan Z. Effects of interfacial on condensation heat transfer (in Chinese). Dissertation for Doctoral Degree. Dalian: Dalian University of Technology, 2006 [兰忠. 界面效应影响冷凝传热过程研究. 博士学位论文. 大连: 大连理工大学, 2006]

Summary for “倾斜超疏水管外滴状冷凝液滴特性的可视化”

Visualization study on droplet dynamic characteristics in dropwise condensation on inclined super-hydrophobic tube

MA XueHu^{*}, LUO Sha, DU BinGang, WU YuLong, LAN Zhong, HAO TingTing,
LIU Xu & WANG Kai

Liaoning Provincial Key Laboratory of Clean Utilization of Chemical Resources, Institute of Chemical Engineering, Dalian University of Technology, Dalian 116024, China

^{*} Corresponding author, E-mail: xuehuma@dlut.edu.cn

Steam condensation with non-condensable gas exists widely in petro-chemical, power plant and seawater desalination processes. Super-hydrophobic surfaces with high contact angle could be an promising condensing surface to promote DWC and enhance heat transfer. As pure steam condensing droplet completely occupies micro/nano-structures of super-hydrophobic surfaces, super-hydrophobic function becomes “invalid”. For stream-air mixture vapor, the non-condensable gas would occupy the micro/nano-structures instead of water. Droplets form Cassie or transition wetting mode, holding or partly holding super-hydrophobic feature. Inclination angle of the tube can influence the shape, size and dynamic characteristics of the condensing droplets, thus changing the heat transfer performance. Therefore, for getting deeply insights of the effect of the non-condensable gas on condensation heat transfer, it is necessary to study the condensing drops characteristics on super-hydrophobic tube for different inclined angles.

According to dropwise condensation model, increasing contact angle hysteresis, departure droplet size, sweeping period would reduce the condensation heat transfer efficiency. In this paper, dropwise condensation is performed on super-hydrophobic copper tube, departure droplet size, sweeping period and the phenomenon of contact angle hysteresis are thoroughly studied and are compared with the case of hydrophobic surface or pure steam to explore the influence of inclined angle and surface wettability on droplet dynamics to achieve condensation heat transfer enhancement.

The experimental result shows:

(1) On the top of copper tube, for the condensation of steam with 10% non-condensable gas, the contact angle hysteresis on super-hydrophobic surface is smaller than that on hydrophobic surface. Compared with pure steam condensation on super-hydrophobic surface, the contact angle hysteresis of mixed steam is smaller because the non-condensable gas fills the micro/nano-structures. However, on the middle and bottom parts of the tube, the contact angle hysteresis on super-hydrophobic surface is greater than that on hydrophobic surface for the condensation of both pure steam and mixed steam. This phenomenon indicates that the contact angle hysteresis is determined by surface wettability instead of inclination angle.

(2) The departure droplet size on super-hydrophobic surface increases with the inclination angle and the opposite trend is found on hydrophobic surface. With the increase of inclination angle, the support force provided by the tube would increase and change direction. So the wettability of the surface and departure droplet size would be changed.

(3) The sweeping period of droplet on super-hydrophobic surface is longer because the micro/nano-structures increase the adhesion between the surface and the droplets. With the increase of the inclination angle, the sweeping period decreased slightly, shorter than the sweeping time when the tube is vertical. The sweeping period of vapor with non-condensable gas condensation is greater than that of pure steam. The presence of non-condensable gas increases thermal resistance, thus slowing down the drop growth rate and increasing the sweeping period.

To sum up, on the top of copper tube, the contact angle hysteresis on super-hydrophobic surface is smaller than that on the hydrophobic surface. However, the totally opposite trend is found on the middle and bottom parts of the tube. The departure droplet size on super-hydrophobic surface increases with the inclination angle. The sweeping period of droplet on super-hydrophobic surface is longer. This work offers a new avenue to further enhance heat transfer of condensation with non-condensable gas.

dropwise condensation, super-hydrophobic, non-condensable gas, inclination angle, contact angle hysteresis, departure droplet size, sweeping period

doi: 10.1360/N972016-00694