低压蒸汽滴状冷凝中液滴脱落滞后效应

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摘要 利用界面结构效应实现蒸汽滴状冷凝对能源动力系统的高效化和集成化具有至关重要的作用. 深入认识液滴动态特性对传热性能的影响有利于探究低压蒸汽冷凝中传热控制机理和研发高效紧凑的传热强化技术. 本文系统地研究了蒸汽滴状冷凝中液滴脱落特性, 提出了低压蒸汽冷凝液滴脱落滞后效应. 随着蒸汽压力降低, 冷凝液滴黏度增加, 引起自身脉动特性下降, 接触线移动受阻, 接触角滞后现象明显, 导致脱落尺寸明显增加而脱落速度大大降低. 与常压蒸汽冷凝中液滴的快速启动连续下落不同, 低压蒸汽冷凝中液滴长至脱落尺寸后表现出了“阶跃式”下落的现象, 即液滴脱落滞后效应. 在液滴整个生命周期中, 低过冷度时液滴生长速度控制着传热过程, 而高过冷度时液滴脱落滞后延缓了表面更新, 降低了有效换热面积, 成为了控制传热过程的因素. 通过液滴脱落效应解释了传热通量随过冷度非线性增加现象的内在机理, 明晰了蒸汽冷凝传热控制机制, 为低压蒸汽冷凝传热强化指明了方向.

关键词

滴状冷凝
低压蒸汽
液滴脱落
动态特性
滞后效应

低压蒸汽冷凝过程广泛地存在于工业生产中, 其过程强化可以大大提高相关设备的运行效率, 如火力发电^[1]、海水淡化^[2]、水回收^[3]以及热能系统^[4-7]. 蒸汽冷凝模式通常由表面润湿性和操作条件决定. 其中, 滴状冷凝传热模式具有更小的传递热阻和更高的传热效率, 引起了许多研究者的关注. 蒸汽滴状冷凝是一个伴随着液滴核化、生长、合并和脱落的动态循环过程. 相关研究表明, 表面性能^[8,9]、蒸汽流速^[10]及不凝性气体^[11]等因素对滴状冷凝传热过程有着重要影响.

对于常压蒸汽滴状冷凝, 已存在较完善的理论体系和较系统的实验研究, 而针对低压蒸汽冷凝过程, 特别是低压蒸汽滴状冷凝过程缺乏系统的研究, 且现有的滴状冷凝传热模型并不能很好地描述低压蒸汽滴状冷凝中出现的特定物理现象, 如液滴尺寸分布与演化、液滴动态特性等^[12]. Tanaka^[13]研究了克努森数对低压蒸汽滴状冷凝传热的影响, 发现核化液

滴的特征尺寸和分子自由程相近. Vemuri和Kim^[14,15]考察了不同压力下蒸汽滴状冷凝和膜状冷凝的传热性能, 认为低压蒸汽滴状冷凝传热性能的下降是由气液界面传质热阻的增加引起的, 但缺乏直接实验结果的支撑. 此外, 相关研究者测试了较宽压力范围内的蒸汽滴状冷凝传热性能, 但传热数据分散, 不具有有一致性^[16-19]. 由此可见, 大多数研究集中在表面性能对宏观传热的影响, 缺乏对蒸汽冷凝过程微观机理的深入分析, 特别是蒸汽压力对液滴动态特性的影响机制和定量地解释低压蒸汽冷凝传热控制机理.

随着观测技术的不断发展, 利用高速CCD和ESME等可视化手段可以准确地获取蒸汽冷凝中液滴行为的动态细节, 有利于探求蒸汽滴状冷凝传热性能的内在机制^[20-24]. Anand和Son^[25]利用ESEM研究了低压蒸汽冷凝环境中液滴的生长过程, 推算出气液界面冷凝系数为0.8. Boreyko和Chen^[26]在真空环境下观测了蒸汽冷凝中微液滴的合并过程, 提出了

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液滴运动机制. Chen等人^[27]研究了表面结构形貌对液滴脱落和液滴分布密度的影响,认为液滴脱落过程对滴状冷凝传热有重要作用. Yamali和Merte^[28]研究了常压条件下液滴脱落的冲刷效应对传热性能的影响. 综上所述,借助可视化手段来分析低压蒸汽下冷凝液滴动态行为可以为定量地解释低压蒸汽滴状冷凝传热特性奠定基础,而相关研究并未见报道.

本文系统地研究蒸汽滴状冷凝中液滴脱落特性,考察蒸汽压力对液滴脱落形态、脱落尺寸和脱落速度的影响,分析液滴脱落过程的微观物理机制,为合理解释蒸汽滴状冷凝传热通量随过冷度非线性增加的现象和低压蒸汽冷凝传热控制机理提供理论依据.

1 实验

(i) 实验装置. 主要由蒸汽发生系统、冷凝室、后冷器及冷却水循环系统组成,如图1所示. 结合真空压力传感器(KEYENCE AP-31A, 精度0.1 kPa)和麦氏真空计(PM-2型, 精度 $\pm 40\%$)记录系统压力. 采用高精度热电偶(精度0.03)测量蒸汽温度及冷凝块内部温度梯度分布,从而计算冷凝表面温度、过冷度及表面传热性能. 利用Agilent34970A数据采集系统监测和记录数据,包括蒸汽压力、过冷度、不凝气含量、热通量及传热系数等相关参数.

(ii) 实验流程. 在保证系统气密性的基础上,采用严格的排除不凝气程序,并实时监测系统不凝气含量,保证纯蒸汽的环境. 根据表面过冷度的改变,即测试表面的传热通量,调整后冷器冷却介质流

量,来实现冷凝室的目标压力,并保证压力稳定^[12]. 具体数据处理过程见文献[29]. 实验计算数据误差采用相关处理方法^[30]. 为了验证实验系统的有效性,在光滑紫铜表面测试了膜状冷凝传热性能,实验值与计算值偏差在10%以内,认为该系统测量及数据处理方法是可靠的.

(iii) 表面制备与表征. 选用十八烷基硫醇作为疏水表面促进剂,将经打磨抛光后的紫铜样品块浸泡在 2.5 mmol L^{-1} 的十八烷基硫醇乙醇溶液中,形成紫铜基疏水表面.

如图2所示,SEM图像(Quanta200, FEI)给出了表面结构形貌,整体较平滑,表面无微纳米结构存在. 利用接触角测量仪(OCA20, Dataphysics)测试了表面接触角、前进角及后退角.

2 结果与讨论

在疏水表面上,液滴经过蒸汽直接冷凝和合并长大到一定尺寸,所受重力会克服表面黏附力向下脱落,形成新的空白表面,开启下一次生长过程. 由于大液滴具有很大的热阻,认为其覆盖的表面不传热,故脱落液滴的尺寸和停留时间对冷凝表面的有效传热面积有重要影响. 本文考察了蒸汽压力对液滴脱落形态、脱落尺寸、脱落速度及生长周期的影响.

2.1 蒸汽压力液滴脱落形态的影响

如图3所示,在低压蒸汽冷凝中,液滴表现出不同与常压蒸汽冷凝的液滴脱落形态和动态特性. 在

图1 (网络版彩色)实验装置流程及冷凝室结构

Figure 1 (Color online) Experimental apparatus and condensing chamber

图2 表面形貌与润湿性. (a) SEM 表面形貌图像; (b) 表面接触角
Figure 2 Surface morphology and wettability of hydrophobic copper surface. (a) SEM image; (b) contact angle

$P_v=1.5$ kPa时, 液滴呈现较完美的半球形, 伴随着液滴下落三相接触线缓慢收缩, 表现出强烈的黏滞作用, 液滴自由表面平滑, 不存在明显脉动. 这主要是因为对于饱和蒸汽冷凝而言, 在相同的过冷度条件下, 随着蒸汽压力下降, 蒸汽温度迅速降低. 冷凝液滴的温度介于蒸汽温度与壁面温度之间, 低压蒸汽冷凝时液滴温度降低, 引起了液滴黏度的增加, 约为常压蒸汽冷凝液滴的5倍, 增加了移动中的黏性耗散, 削弱了液滴自身动能, 降低了液滴运动能力. 而在常压蒸汽冷凝中, 液滴的下落伴随着强烈的自身脉动, 并引发三相接触线在冷凝表面上周期性地收缩与扩张, 能够克服接触线黏滞带来的局部能垒, 大大地减小了接触角滞后^[31,32], 提高了运动能力, 有利于快速脱落, 增加表面凝液的更新频率, 减小了整个冷凝表面的传递热阻, 促进蒸汽的快速冷凝传热.

2.2 蒸汽压力对液滴脱落半径的影响

根据竖直冷凝表面上液滴静态受力分析, 可以

图3 (网络版彩色)蒸汽压力对冷凝液滴脱落形态的影响. (a) $P_v=1.5$ kPa, $\Delta T=4$ K; (b) $P_v=101$ kPa, $\Delta T=4$ K
Figure 3 (Color online) Effect of steam pressure on dynamic morphology of falling droplets. (a) $P_v=1.5$ kPa, $\Delta T=4$ K; (b) $P_v=101$ kPa, $\Delta T=4$ K

得到液滴脱落半径为^[33,34]

$$r_{\max} = \left[\frac{6c(\cos \theta_R - \cos \theta_A) \sin \theta}{2 - 3 \cos \theta + \cos^3 \theta} \cdot \frac{\sigma}{\pi \rho g} \right]^{1/2}, \quad (1)$$

其中, σ 是液滴的表面张力, θ , θ_A , θ_R 分别是平衡接触角、前进角和后退角, 参数 c 与接触线的变形有关.

图4给出了蒸汽压力和表面过冷度对液滴脱落尺寸的影响规律. 可以看出, 随着蒸汽压力下降, 液滴脱落尺寸增加, 与常压蒸汽相比, $P_v=1.5$ kPa时液滴脱落尺寸增加了29%. 此外, 模型预测的准确性随蒸汽压力降低而下降. 这是由于, 一方面模型计算选用的是非冷凝条件下测量的接触角数据, 而在蒸汽冷凝中脱落液滴与周围微小液滴的不断合并会增加接触角滞后, 引起脱落半径增加, 这个作用在低压和常压蒸汽冷凝中均存在; 另一方面, 脱落模型将液滴视为静态进行受力分析, 忽略了常压冷凝中液滴脉动对接触角滞后的减弱作用. 在两方面的作用下, 模型预测误差随着蒸汽压力降低而增加. 此外, 随蒸汽压力下降, 冷凝表面上液滴生长速度减小, 脱落频率下降, 停留时间的增加会引起更大的脱落尺寸^[35].

2.3 蒸汽压力对液滴脱落速度的影响

图5给出了 $\Delta T=4$ K, $P_v=101$ kPa和 $P_v=1.5$ kPa时液滴脱落过程的系列图像以及脱落半径和脱落距离随时间的变化规律. 如图5(a)所示, 液滴从启动脱落开始, 在0.06 s内下落了8.25 mm. 液滴下落曲线平滑, 即一旦启动下落表现出连续下滑, 在下落中伴随着液滴尺寸增加. 液滴脱落形态的分析表明, 常压蒸汽

图4 (网络版彩色)蒸汽压力和过冷度对脱落尺寸的影响. (a) $P_v=1.5$ kPa; (b) $P_v=9.6$ kPa; (c) $P_v=31$ kPa; (d) $P_v=60$ kPa; (e) $P_v=101$ kPa
Figure 4 (Color online) Effect of steam pressure and surface subcooling on departure radius. (a) $P_v=1.5$ kPa; (b) $P_v=9.6$ kPa; (c) $P_v=31$ kPa; (d) $P_v=60$ kPa; (e) $P_v=101$ kPa

图 5 (网络版彩色)液滴下落距离和半径随脱落时间的变化. (a) $P_v=101$ kPa, $\Delta T=4$ K; (b) $P_v=1.5$ kPa, $\Delta T=4$ K
Figure 5 (Color online) Evolution of falling distance and droplet radius with departure time. (a) $P_v=101$ kPa, $\Delta T=4$ K; (b) $P_v=1.5$ kPa, $\Delta T=4$ K

冷凝中,液滴合并引发的脉动过程促进接触线克服局部能垒,有利于接触线的收缩与扩张,减小了冷凝液滴底部与壁面的有效接触面积,降低了脱落阻力,促进了液滴启动下落后迅速脱落.与常压条件相比,低压蒸汽冷凝中液滴脱落速度大大减小,在0.9 s内下降了5.2 mm,如图5(b)所示,并且脱落过程表现出了“阶跃式”下降的特征.通过对比脱落液滴各个时刻的位置和尺寸可以看出,伴随着每次液滴尺寸长大,即合并长大过程,液滴发生瞬时的快速移动,而后缓慢下降,如此循环.这是因为,一方面,当脱落液滴与前进方向的液滴发生合并时,下部三相线瞬间外扩,向下的合力增加,液滴表现出快速向下移

动;另一方面,较大的黏度增加了液滴三相线移动过程的能量耗散,导致液滴脱落在固液界面阻力的作用下减速运动.因此,液滴合并只是导致瞬间的移动,并不能引发液滴的连续移动,低压蒸汽冷凝环境中的液滴表现出了缓慢下降的现象.

如图6所示,通过统计不同操作条件下的可视化图像,定量地分析了蒸汽压力和表面过冷度对液滴脱落速度的影响规律.从液滴启动脱落开始,计算了液滴下落一定距离所需的时间,得到液滴的平均脱落速度.结果表明,随着蒸汽压力降低,液滴脱落速度迅速下降,而表面过冷度对液滴脱落速度影响表现不明显.在液滴整个生长周期中,低过冷度时,液滴生长速度缓慢,液滴脱落滞后引起有效换热面积减小对传热过程影响减弱,故表面过冷度控制着传热过程;而高过冷度时,液滴快速生长,液滴脱落滞后大大地延缓了表面更新,降低有效换热面积,严重影响了传热过程.因此,在不同表面过冷度范围内,液滴脱落滞后效应对传热有着不同的控制机理.在相关研究中^[8,9,35,36],同样发现了滴状冷凝传热系数随过冷度增加而下降的趋势,但并没有给出合理的解释.这里通过引入液滴脱落滞后效应,阐明了不同过冷度范围内的冷凝传热控制机制,解释了传热通量随过冷度非线性增加现象的内在机制.

3 结论

本文研究了低压蒸汽滴状冷凝中液滴脱落特性,

图 6 (网络版彩色)蒸汽压力和过冷度对脱落速度的影响
Figure 6 (Color online) Effect of steam pressure and surface subcooling on departure velocity of condensing droplets

考察了蒸汽压力对液滴脱落形态、脱落尺寸和脱落速度的影响,提出了液滴脱落滞后效应.主要得到以下结论.

(1) 随着蒸汽压力下降,液滴动态性能下降,自身脉动减弱,脱落尺寸明显增加.与常压下液滴的快速连续下落不同,低压下液滴表现出了“阶跃式”的缓慢下落过程,降低了表面有效传热面积.

(2) 随着过冷度增加液滴生长速度增加而脱落速度基本不变:即低过冷度时液滴生长速度控制传热过程,而高过冷度时液滴脱落滞后效应延缓了表面更新,成为了传热过程的控制因素.

(3) 引入液滴脱落滞后效应,解释了传热通量随过冷度非线性增加现象的内在机理,有助于探明低压蒸汽滴状冷凝传热控制机制.

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Retention effect of droplet departure in dropwise condensation at low steam pressure

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Dropwise condensation caused by interfacial effects plays a crucial role in the thermal efficiency and integration of power production. It is important to understand the effect of droplet dynamic characteristics on heat transfer performance for the controlling mechanism of dropwise condensation heat transfer at low steam pressure and the development of efficient heat transfer techniques. Based on droplet departure characteristics in dropwise condensation at different steam pressures, the droplet departure retention effect at low pressure was proposed in this paper. Due to the increase of condensate viscosity at low steam pressure, the pulsation of droplet surface weakened and the contact angle hysteresis became apparent. Condensed droplets grew larger and moved more slowly in the departure process at low pressure compared to that at atmospheric pressure. Meanwhile, the droplet moved quickly downward once it grew to the departure size at atmospheric while the droplet exhibited a slow stick-slip motion although it reached the departure size at low pressures, which was called the droplet departure retention effect. In a growth cycle of condensed droplet, the heat transfer process was controlled by the droplet growth rate in small surface subcooling range. However, the droplet departure retention delayed the surface renewal reducing the effective heat transfer area in large surface subcooling range. Furthermore, droplet departure retention was introduced to explain the inherent mechanism of the nonlinear increase of heat flux varying with surface subcooling. This work is beneficial to clear the controlling mechanisms of dropwise condensation heat transfer and offer a new avenue to further enhance heat transfer of dropwise condensation at low steam pressure.

dropwise condensation, low pressure steam, droplet departure, dynamic characteristics, retention effect

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