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热力循环

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闭式循环喷雾冷却传热特性实验研究

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摘 要: 分别以蒸馏水和无水乙醇为工质在闭式循环喷雾冷却系统上研究了喷雾流量、表面结构、喷雾工质对传热性能的影响。从对流换热和相变换热比例关系的角度对实验数据进行了整理。结果表明: 随喷雾流量的增加，热流密度增加、相变换热份额降低。当水喷雾流量为 227.1 g/min、表面温度为 74.32 ℃时，热流密度达到 6.8×10^5 W/m^2; 表面温度对换热有较大影响，温度越高换热性能愈强，无水乙醇的换热始终强于蒸馏水，特别是表面温度较高时，强化换热效果更为明显; 其相变份额同样始终大于蒸馏水，表面温度为 50 ℃、流量同为 27.52 g/min 时，蒸馏水的相变换热份额仅为 20.4%，而无水乙醇的达到 55.5%。微结构表面虽然减弱了对流换热能力，但减薄了液膜厚度，增强相变换热能力，使换热效果大幅提升。给出了反映表面温度影响的无量纲准则方程。

关 键 词: 喷雾冷却; 喷雾流量; 热流密度; 相变换热份额

中图分类号: TK124 **文献标识码**: A

引 言

喷雾冷却被认为是最有效率最有前景的冷却方式。在较小的过热度下，用水作为冷却工质，在开放条件下，极限热流密度 (CHF) 可达 1 200 W/cm^2 [1 ~ 2] 。

目前，关于喷雾冷却机理仍没有形成共识，这主要是因为影响喷雾冷却的因素众多。影响喷雾冷却的因素有: 喷雾特性、冷却剂自身的物理性质、热表面特征、环境特性等 [3 ~ 6] 。国内近年也有一些单位积极开展该方面研究 [7 ~ 9] ，但大多数只整理热流密度与表面过热度之间的简单曲线。一般认为喷雾冷却的传热机理包括 3 种: 对流换热、液膜蒸发、核态沸腾，后两者统称为相变换热 [5] 。但目前没有系统研究相变换热份额、比较表面结构对相变换热影响。因此，本研究从相变换热和对流换热比例关系的角度分析工质性质、表面结构等因素对喷雾换热影响，研究喷雾强化换热原因。

1 实验系统

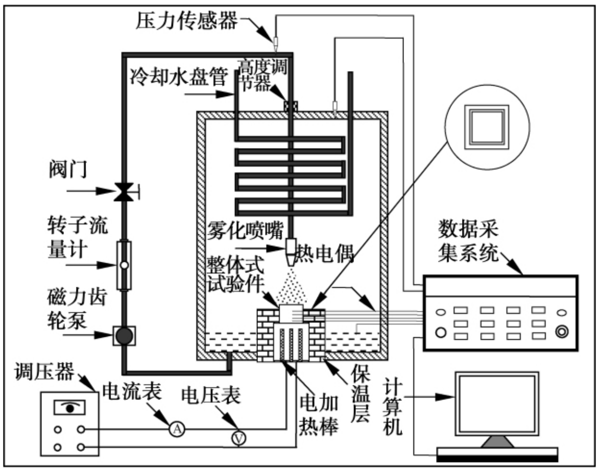

图 1 实验系统图
Fig. 1 Test system diagram

喷雾冷却回路系统如图 1 所示，包括整体式实验件、喷雾腔、喷射系统、加热系统、冷却系统和数据采集系统。实验件是直接受热面积为 2 cm × 2 cm 的可更换表面。实验中工质采用闭式循环，喷雾腔底部液池中的工质由齿轮泵抽吸，通过流量计、调节阀、雾化喷嘴对实验件进行喷雾冷却，而后工质流回液池。实验中采用差值的办法计算相变换热份额，即总热流减去对流换热热流，因此精却计算对流换热份额显得尤为重要，为此需要精确测量喷雾后离开加热面液体温度，采用的办法是在加热面边缘基座表面周向开槽，槽中布置多只高精度热电偶; 同时

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控制好喷雾高度，使喷雾量完全落在加热面范围内，保证喷雾蒸发后剩余液体全部沿加热面向外流动，冲刷开槽中的热电偶。实验中喷射高度均为 1 cm。

2 实验数据处理

实验件热流密度可由沿加热件高度方向上布置的两排热电偶给出的温度推得：

$$q = \lambda \frac{t_2 - t_1}{10000\delta_2} \tag{1}$$

式中：q—热流密度，W/cm^2；λ—紫铜实验件导热系数，W/(m · ℃)；t_1、t_2—上、下排热电偶测得的温度均值，℃；δ_2—两排热电偶间距，m。

根据傅里叶定律，实验件表面温度为：

$$t_w = t_1 - (10000q\delta_1/\lambda) \tag{2}$$

式中：t_w—实验件表面壁温，℃；δ_1—上排热电偶与实验件表面之间距离，m。

喷雾冷却换热系数为：

$$h = q/(t_w - t_j) \tag{3}$$

式中：h—换热系数，W/(cm^2 · ℃)；t_j—喷雾流体温度，℃。

对流换热量表示喷雾液体离开加热面后，由于温度升高而带走的热量，可用对流热流密度表示：

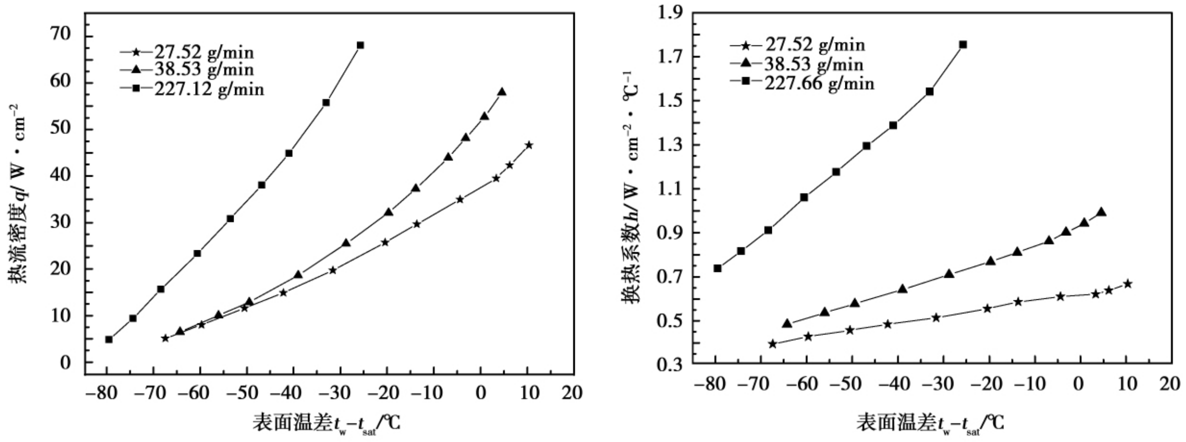
$$q_c = mc_p(t_{out} - t_{in})/60000S \tag{4}$$

式中：m—喷雾流量，g/min；c_p—工质定压比热，J/(kg · ℃)；t_{in}、t_{out}—喷雾前后工质温度，℃；S—加热面投影面积，cm^2。

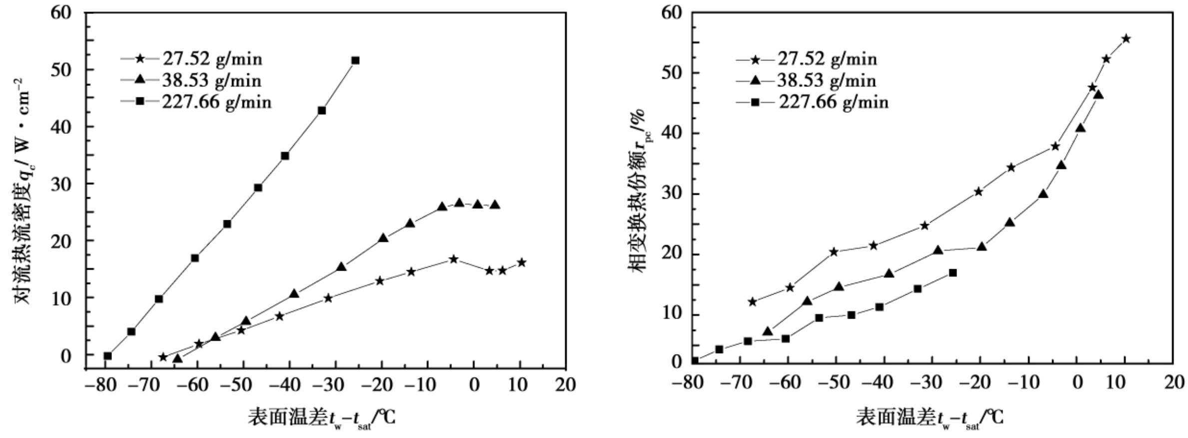
喷雾带走的热量包括对流换热量带走的显热及液体相变带走的潜热，总热量扣除式(4)的对流换热量即为相变换热量，故相变换热所占比例为：

$$r_{pc} = \frac{q - q_c}{q} \times 100 \tag{5}$$

式中：r_{pc}—相变传热占总传热份额，%。



(a) 喷雾流量对热流密度影响　　(b) 喷雾流量对换热系数影响



(c) 喷雾流量对对流热流密度影响　　(d) 喷雾流量对相变份额影响

图 2　喷雾流量对换热影响

Fig. 2 Influence of the spray flow rate on the heat exchange

3　实验结果及讨论

3.1　喷雾流量对换热性能的影响

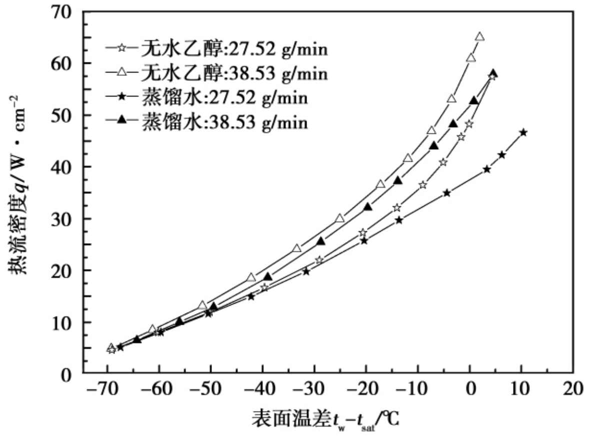
图2为喷雾水流量对光面换热性能的影响规律。由图2(a)可知,随着喷雾流量增加,热流密度增加。这是因为在所有流量下,喷嘴雾化角均为60°,故而喷射的液体全部落在加热面上,因此喷雾量增加,就意味着喷雾流速增加,附壁流场的流速增加,加热面流体扰动剧烈,从而换热较好。由图2(d)可知,随着喷雾流量增加相变换热份额在降低,这是因为相变换热的根本原因在于能量水平高的水分子逃离液相,而其逃逸的动力取决于液体温度,阻力来源于液膜厚度,相同壁温流量增大时液膜变厚,阻力增加,故而蒸发相对变差,这也就说明随流量大幅增加,换热增强的主要原因在于对流换热的快速增加(图2(c))。图2(b)显示,换热系数随壁温增加而增加,这与传统的强迫对流换热显著不同,这主要是源于喷雾冷却中存在较强的蒸发换热,而蒸发随壁温的增高加快,其换热折算到对流换热中,致使换热系数增大。

喷雾流量为227.1 g/min,表面温度74.32 ℃时,热流密度达到6.8×10^5 W/m^2,换热系数1.75×10^4 W/(cm^2·℃)。而大容器池式沸腾热流密度若想达到此值,表面温度需达到120 ℃左右,可见与池沸腾相比喷雾冷却传热明显强化。

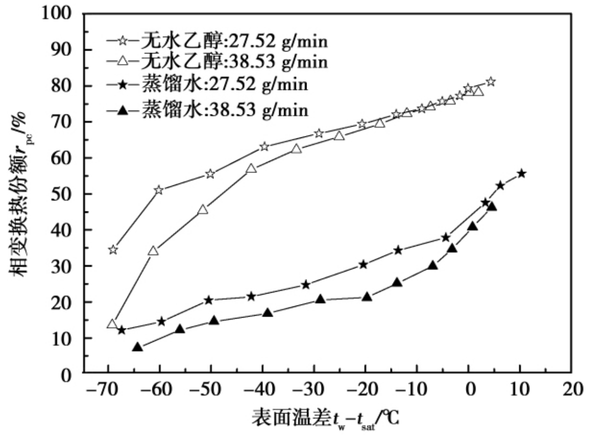
3.2　喷雾工质对换热性能的影响

图3为工质种类对光面换热性能的影响规律。在所有情况下,无水乙醇的换热效果均好于蒸馏水,尤其在表面温度较高时,差别更为明显,如图3(a)所示。其原因主要在于无水乙醇超强的相变换热能力,如表面温度为50 ℃、流量同为27.52 g/min时,蒸馏水的相变换热份额仅为20.4%,而无水乙醇的达到55.5%,效果提升1.72倍之多。因此,即使无水乙醇对流换热较差,综合而言总换热效果仍然好于蒸馏水。而无水乙醇之所以有如此强的相变换热能力,是因为无水乙醇的表面张力明显低于蒸馏水,致使其在加热表面铺展效果较好,液膜厚度较薄,蒸发效果明显提升,如图3(b)所示;同时无水乙醇的沸点较低,仅为78.32 ℃,壁面温度较低时,液膜也接近饱和状态,较早出现小汽泡,扰动液膜能力增强。

综上,喷雾冷却想要取得较高的换热强度,应使表面温度尽量高些,如果表面温度不宜过高,需要选用沸点低的流体作为喷雾工质。但是如果沸点过低、物性与水差别过大,即使有再高的相变换热能力,鉴于对流换热能力太差,也不能取得好的换热效果[10~11]。



(a) 工质对热流密度影响



(b) 工质对相变换热份额影响

图3　喷雾工质对换热影响

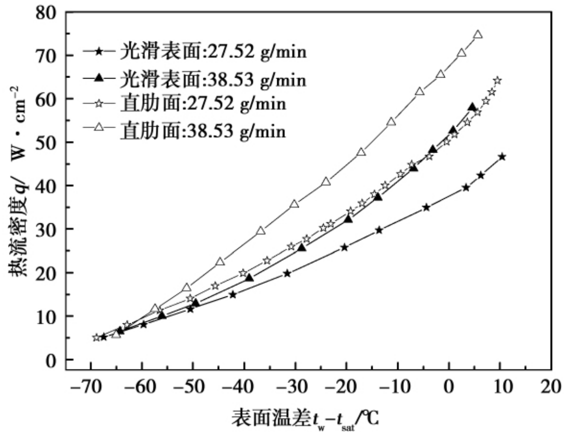
Fig. 3 Influence of the spray working medium on the heat exchange

3.3　表面结构对换热的影响

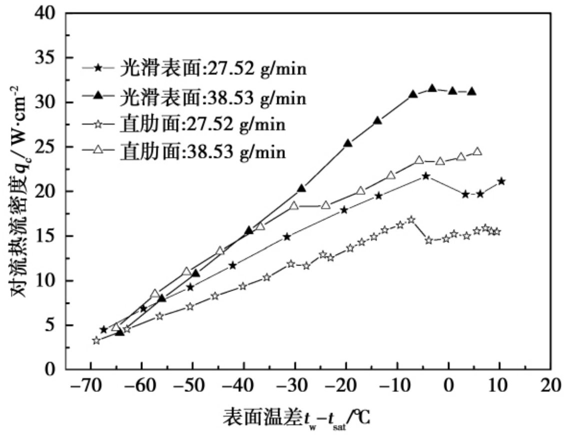
图4为表面结构对换热性能的影响规律,工质为蒸馏水。图中直肋面是在光面上开槽而成,槽宽、间距、深分别为0.3、0.6和0.7 mm。与光面数据对比可知,强化传热效果非常明显,如图4(a)所示。

文献[5,12~13]研究认为:微结构由于增加换热面积,因此对流换热量增加;另外蒸发换热也不同程度增强,所以微结构面能大幅提升换热效果。但这些研究并没有实测对流换热效果,只是根据常规对流换热理论进行的推测。本研究结果表明,微结构确实可以改善喷雾换热能力,但与光滑表明相比,对流换热并没有增加,反而出现不同程度的降低,如

图4(a)、(b)所示。这主要因为，开槽表明虽然面积增加，但由于流体流动的槽道很细小，流动阻力增加更大，使得流体在微结构面上流动速度减慢，所以对流换热变差。由此可见，微结构强化换热的主要因素是相变换热的大幅提升，微槽表面有大量槽道，喷雾液体落入槽面后，大量液体必然浸入槽道中，同时微结构间毛细力可使液滴更为有效扩散，表面微结构槽间的毛细力可有效抵制由喷雾剪切力而造成的液膜过早破裂[5]，如此可显著减薄液膜厚度，减小液体分子逃逸阻力，所以相变换热能力会明显改善，最终提升换热效果。



(a) 表面结构对热流密度影响



(b) 表面结构对对流换热影响

图4 表面结构对换热影响

Fig. 4 Influence of the surface structure on the heat exchange

但由图4(b)可见，流量为38.53 g/min、表面温度60 ℃之前，槽面对流换热好于光面，说明微结构增强换热效果与流体在换热表面流动息息相关[12]，并不是所有流量、所有壁面温度时，槽面对流换热均较差，如果流量增加，扰动能力增强，超过槽道的阻力增加，鉴于槽道面换热面积较大，传热可能会提升，但这需要实验进一步验证。

3.4 光面喷雾冷却无量纲关系式

图2～图4均表明相变换热对喷雾冷却的影响不可忽视。推导换热无量纲公式时，以无量纲温度表征液膜相变换热速度的快慢计算：

$$\zeta=(t_w-t_e)/t_b \qquad (6)$$

式中：t_w、t_e、t_b—热表面温度、环境温度和工质沸点。无量纲温度越高相变换热能力愈强。

用雷诺数表征流动对换热的影响，而换热性能由努塞尔数表示，则：

$$Nu=hD/\lambda;\ Re=GD/\mu \qquad (7)$$

式中：h 为换热系数，W/(m^2·℃)；D—喷雾底圆直径，m；G—喷雾质量介质通量，kg/(m^2·s)；λ—工质导热系数，W/(m·℃)；μ—工质动力粘度，Pa·s。

综合如上因素，对流量较小时水的实验数据进行了拟合，得到拟合关系式：

$$Nu=11.865Re^{0.91108}\zeta^{0.42346} \qquad (8)$$

所有实验点均落于拟合式的±15%以内，拟合式表明 Nu 数随着 Re、ζ 的增加成指数关系增长，这与前面的理论分析一致，如图5所示。

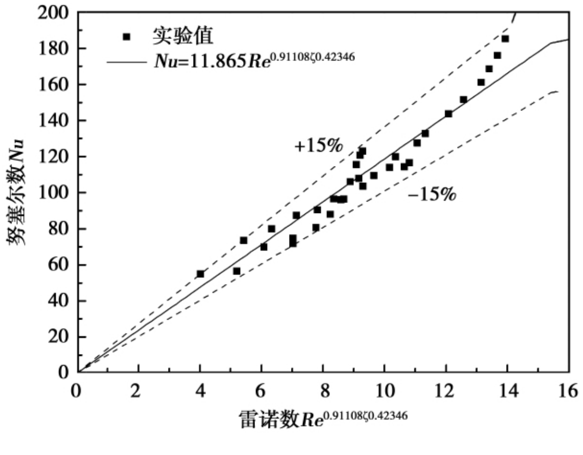


图5 Nu 与 Re、ζ 的关系

Fig. 5 Relationship among Nu, Re and ζ

4 结 论

在闭式循环喷雾冷却实验系统上，研究了喷雾流量、表面结构、工质种类对喷雾冷却传热性能的影响规律，得到结论：

(1) 喷雾冷却热流密度随喷雾流量、表面温度的增加而增加，相变换热份额则随流量增加而降低，

与池沸腾相比,喷雾冷却传热强化非常明显;

(2) 无水乙醇冷却效果明显优于蒸馏水,整个实验表面温度范围内,无水乙醇的相变份额均高于蒸馏水的。喷雾冷却想要取得较高的换热强度,应使表面温度尽量高些,如果表面温度不宜过高,需要选用沸点低的流体作为喷雾工质;

(3) 微结构表面能显著提升换热能力,但对流换热能力与喷雾流量和表面结构关系较为复杂,流量较小时,微结构对流换热反而减弱。

(4) 对水喷雾冷却数据进行了无量纲化处理,得到了包含相变特性的无量纲准则方程。

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(丛　敏　编辑)

信息之窗

Vestas 认为墨西哥具有 10 GW 风力发电潜力

丹麦风力涡轮制造商 Vestas 最近已经签订合同供货 132 台涡轮机,用于 396 MW Marena Renovables 工程项目,该项目建后,将是拉丁美洲最大的风力发电厂。

但是,Adrian Ktzew 公司的墨西哥董事长,认为墨西哥风力发电潜力更大。

该官员说墨西哥在风力发电方面已经走了很长的路,特别是在 Oaxaca 地区,但是他仍然说拉美国家可以很容易地翻倍甚至 3 倍其现有容量。

Ktzew 估计墨西哥风力发电潜力至少 10 000 MW,而且政府已经确定仅在 Oaxaca 地区的目标就达到 2500 MW。

(李春清　供稿)

formance test,error analysis,Taylor series

基于变工况分析的供热机组负荷特性研究 = Study of the Load Characteristics of a Heat-supply Unit Based on an Analysis of Its Off-design Operating Conditions [刊,汉] WU Long,YUAN Qi (College of Energy Source and Power Engineering,Xi′an Jiaotong University,Xi′an,China,Post Code:710049),DING Jun-qi,WANG Xue-tong (Shandong Electric Power Research Institute,Jinan,China,Post Code:250002) // Journal of Engineering for Thermal Energy & Power. – 2012,27(4). –424 ~ 428

At present,there exist universally disputes between power plants and the electric power dispatchment departments concerning the matter how to determine the dispatchment scope of the heat-power load for a heat-supply unit. On the basis of the thermal parameters and characteristics of the heat-supply unit together with its off-design operating condition thermal calculation results,curves showing the relationship of the heat-power load dispatchment were obtained. Through a comparison with the curves showing the heat-power relationship obtained by using the chart of the operating conditions of the unit,it can be found that the curves obtained from the thermal calculation have an enough calculation precision. Moreover,through adopting the thermal calculation method,other factors,which limit the load dispatchment of the unit,can be taken into account properly,thus making the dispatchment scope more rational and reasonable. At the same time,the method in question can effectively predict the influence of a change in the steam extraction parameters on the load dispatchment of the unit. Through a comparison,it can be found that for a unit with a relatively high heat supply steam extraction pressure,to properly reduce the steam extraction pressure can enhance the power dispatchment scope of the unit. The method under discussion can offer a sound and correct solution to the load dispatchment problem between a power plant and its heat-power dispatchment department. **Key words:** heat supply unit,off-design operating condition calculation,load dispatchment,steam extraction pressure

闭式循环喷雾冷却传热特性实验研究 = Experimental Study of the Atomization Cooling and Heat Transfer Characteristics of a Closed Type Cycle [刊,汉] ZHANG Wei,WANG Zhao-liang,XU Ming-hai (College of Storage,Transportation and Architectural Engineering,China Petroleum University,Qingdao,China,Post Code:266555) // Journal of Engineering for Thermal Energy & Power. – 2012,27(4). –429 ~ 433

With distilled water and anhydrous alcohol serving as the working medium respectively,studied was the influence of the atomization flow rate,surface structure and atomization working medium on the heat transfer performance in a closed type cycle atomization and cooling system. For the first time from the viewpoint of convection-based heat exchange and phase-change heat exchange proportions, the authors trimmed and analyzed the test data. It has been found that with an increase of the atomization flow rate, the heat flux density will increase while the phase-change heat exchange proportion will decrease. When the water atomization flow rate is 227.1 g/min and temperature on the surface is 74.32℃, the heat flux density will hit 6.8×10^5 W/m^2. The temperature on the surface has a relatively big influence on the heat exchange. The higher the temperature, the better the heat exchange performance. The heat exchange of anhydrous alcohol is always superior to that of distilled water, especially when the temperature on the surface is relatively high, the intensified heat exchange effectiveness will be more evident. The phase-change heat exchange proportion of the anhydrous alcohol is also invariably higher than that of distilled water. When the temperature on the surface is 50℃ and both flow rates are concurrently 27.52 g/min, the phase-change heat exchange proportion of distilled water is only 20.4% but that of anhydrous alcohol reaches 55.5%. Although the micro-structure surface weakens the convection-based heat exchange capacity, it thins the liquid film thickness and enhances the phase-change heat exchange capacity, thus greatly upgrading the heat exchange effectiveness. A non-dimensional criterion equation reflecting the influence of the temperature on the surface was given. **Key words:** atomization cooling, atomization flow rate, heat flux density, phase-change heat exchange proportion

管内插入扭带及螺旋线圈的传热与阻力特性实验研究 = Experimental Study of the Heat Transfer and Resistance Characteristics of a Tube Internally Inserted by a Twisted Tape and a Spiral Coil **刊,汉**

HAN Jiguang, WU Xin, ZHOU Yi (College of Energy Source and Environment, Southeast University, Nanjing, China, Post Code: 210096), ZHAN Yue (Nanjing Shengnuo Heat Pipe Co. Ltd., Nanjing, China, Post Code: 210009) // Journal of Engineering for Thermal Energy & Power. – 2012, 27(4). –434 ~ 438

Experimentally studied were the heat transfer and resistance characteristics of a tube internally inserted by a twisted tape and a spiral coil with air serving as the working medium. In the scope of turbulent flow, i.e. $3000 < Re < 22000$, test data were obtained by using a tube internally inserted with a twisted tape of five kinds of structural parameters, a spiral coil ($p = 20$ mm, $e = 2$ mm) and a combination of a twisted tape ($Y = 4.76 \sim 9.52$, $X = 0.714 \sim 0.952$) and a spiral coil ($p = 20$ mm, $e = 2$ mm). It has been found that to internally insert a twisted tape can increase Nusselt Number by 32% – 56% and f by 157% – 208% and to internally insert a spiral coil can increase Nusselt Number by 70% – 88% and f by 705% – 808% while to internally insert a combination of a twisted tape and a spiral coil can increase Nusselt Number by 117% – 133% and f by 859% – 893%, indicating that the internally inserted object can obviously increase the in-tube heat exchange coefficient of air and in the meantime, however, it