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单回路紫铜—水脉动热管传热性能的实验研究

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摘 要: 实验研究了单回路紫铜—水脉动热管在水冷方式和定传热功率时,冷却水流量、倾角、管径和充液率4种因素对热管传热性能,包括管壁测点温度、冷热段均温、传热温差、传热热阻和温度振幅的影响规律,得到提高传热性能的一些措施。结果显示: 水平放置的单回路脉动热管无法启动; 30°以上倾角管内可产生振荡,增加倾角可降低传热热阻; 定加热功率下,冷却水流量存在最佳值,过大和过小都会增加传热热阻; 在脉动热管允许管径范围内,增加管径可大大降低传热热阻; 相同传热功率时,30%充液率热管的传热热阻明显低于70%充液率管; 小而均匀的壁温振荡比大幅锯齿状振荡时的传热性能好。

关 键 词: 单回路脉动热管; 充液率; 管径; 传热性能

中图分类号: TK172.4 **文献标识码**: A

符号说明

d/D——内/外径/(mm);
G——水流量/L·h^{-1};
l——热管长度/mm;
P——传热功率/W;
R——传热热阻/℃·W^{-1};
t——温度/℃;
t_0——环境温度/℃;
x_v——充液率/%;
t_x——传热温差/℃;
θ——倾角/(°);
下标
a——绝热段;
c——冷凝段;
e——蒸发段。

引 言

脉动热管(OHP)是20世纪90年代初由日本的ARCHI提出和发明的一种新型热管。其型式可分为两种: 环路型和非环路型。工作原理是: 当热管管径足够小时,真空条件下封装在管内一定量的工作介质将在管内形成汽液相间的柱塞。一端加热,使工质升温、升压、沸腾、汽化和膨胀,推动介质向冷凝段流动,冷却段使工质降温降压、冷凝、收缩和回流,期间产生轴向振荡、循环流动和相变,从而实现热量的传递[1]。脉动热管优点很多; 如体积小,结构简单,成本低,无须动力驱动,传热系数高,没有普通热管的传热极限等。

影响脉动热管传热性能的因素很多,如管径、管长、加热段和冷却段长度比例、管弯数、倾角,冷却条件等。目前,各国学者对脉动热管传热机理和传热性能的研究多采用实验方法,一些因素对传热性能的影响规律虽有一定认同,但由于研究者的实验条件、实验目的和手段的不同,得到的结论仍差别较大。

目前,单回路脉动热管实验研究的报道和文献很少,本研究对定加热功率水冷却单回路脉动热管进行试验研究,得出冷却水流量、倾角、管径和充液率4种因素对热管传热性能的影响特性,对比分析热管各测点温度、冷热段均温、传热温差、传热热阻和壁温振荡特性,得到提高单回路热管传热性能的一些有价值的结论。

1 实验设定

1.1 实验装置

本实验装置包括5个部分: 实验热管、水冷却装置、加热装置、测温和数据采集系统。水冷却装置由双层真空玻璃水夹套,转子流量计,进出水软管和控制阀组成。加热装置包括绝缘电加热丝、可调直流电源、抽真空保温玻璃罩; 测温系统采用E型镍铬-康铜热电偶,一端焊在热管外壁上,另一端接在惠普数据采集仪上,并与电脑连接,装置示意图如图1所示。

实验中,加热段采用绝缘加热丝均匀缠绕定热流加热方式,为减少加热段辐射对流散热损失,热管加热段套上抽真空玻璃保温罩。热管冷却段放到双层抽真空玻璃水冷套中,用软水管连接到水冷套的进出口,再在进水管上接上转子流量计,之后与水箱

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连接,通过水箱控制阀调节水流量。热管及测点分布图如图 2 所示。

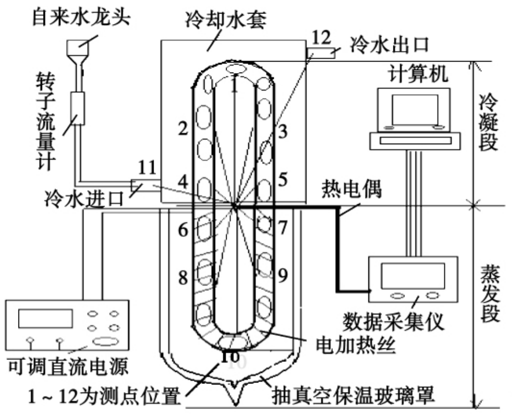

图 1　水冷试验装置示意图

Fig. 1 Schematic drawing of a water cooling test device

其中 1 ~5 为冷却段 5 个测点;6 ~10 为加热段的 5 个测点。

1.2　实验方案

实验方案分为 4 组,分别对应 3 种冷却水流量、4 个倾角、2 种管径和 2 种充液率的热管。通过定加热功率的对比实验,研究不同因素对热管传热性能的影响。

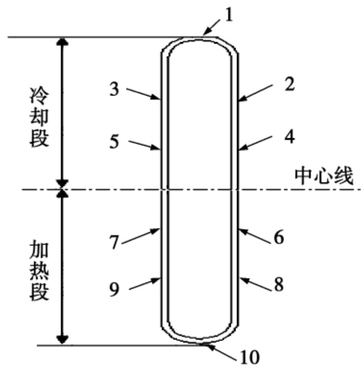

图 2　热管及测点布置示意图

Fig. 2 Schematic drawing of the arrangement of heat tubes and measuring points

实验热管基准操作参数为: $x_v = 70\%$, $l = 400$ mm, $t_0 = 24.5$℃, $d/D = 3/4$ mm, $l_e/l = 0.5$, $l_a = 0$ mm, $P = 80$ W。对比方案表如表 1 所示。

表 1　对比实验方案

Tab. 1 Scheme for a contrast test

测试号	方案	对比因素	$G/L\cdot h^{-1}$	$x_v/\%$	d/D(mm)	l/mm	t_0/℃	l_e/l	θ/(°)	P/W
1 2 3	1	流量 G	40 70 100	70	3/4	400	24.5	1/2	90	80
4 5 6 2	2	倾角 θ	70	70	3/4	400	24.5	1/2	0 30 60 90	80
2 7	3	管径 d/D	70	70	3/4 4/6	400	24.5	1/2	90	80
8 2	4	充液率 x_v	70	30 70	3/4	400	24.5	1/2	90	80

表 1 中 70 L/h 对应的水流速为 1.22 cm/s,40 L/h 对应的流速为 0.7 cm/s,110 L/h 对应的流速为 1.92 cm/s。

测试号为 2 的实验满足基准测试条件,每组对比方案都是与 2 号测试的传热性能做对比。

1.3　数据处理

通过对热管上均匀布置的 10 个测点壁温的测试及数据处理,计算出 5 个反映热管传热特性和振荡特性的参数: 冷凝段均温 t_c、蒸发段均温 t_e、热管传热温差 $\triangle t_x$、热管传热热阻 R_x 和冷凝段和蒸发段温度平均振幅。其中冷凝段和蒸发段的均温为冷凝段和蒸发段 5 个测点的平均温度,传热温差指蒸发段均温与冷凝段均温的差值,传热热阻指热管内部工质循环传热热阻,是传热温差与传热功率的比值。

2　实验结果及分析

分析了单回路热管在 80 W 加热功率下 4 种影响因素: 冷却流量 G、倾角 θ、管径 d/D 和充液率 x_v 对热管测点温度、冷热段均温、传热温差、传热热阻和温度振幅的影响。

2.1　实验结果

2.1.1　各测点温度

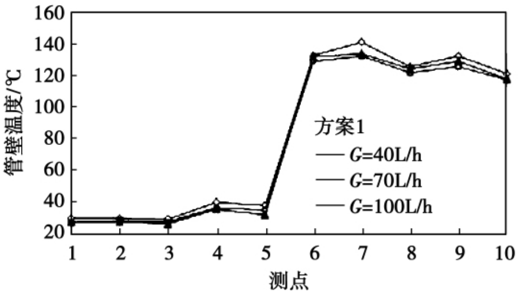

图 3　冷却水流量 G 对管壁各测点温度的影响

Fig. 3 Influence of the cooling water flow rate G on the tubewall temperatures at various measuring points

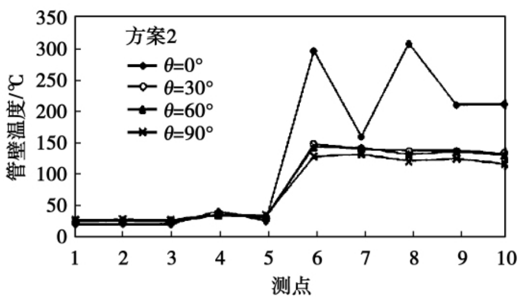

图 4　倾斜角 θ 对管壁各测点温度的影响

Fig. 4 Influence of the inclination angle θ on the tubewall temperatures at various measuring points

图 3 至图 6 显示了 4 因素对 10 个测点管壁温度的影响。其中,冷却水流量对管壁温度影响较小; 倾角中,水平放置的热管,热段 5 个测点温度远远高于其它 3 个倾角热端温度,最高温度达到 320℃左右,说明水平放置的热管没有启动,而当倾角达到 30°以上时,冷热段测点温度基本接近; 管径对热段测点壁温影响较大,且随管径增大,热段测点温度明显降低; 充液率对测点温度的影响表现在,70% 充液率管的热段测点温度明显高于 30% 管,70% 管的冷段温度突变到热段温度,而 30% 管则呈现缓慢变化。

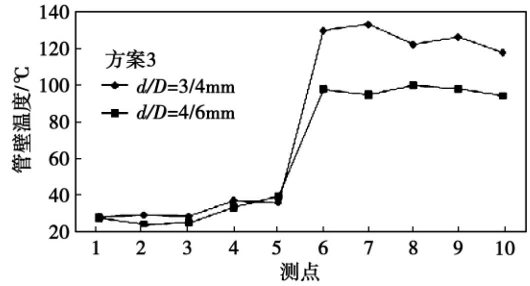

图 5　管径 d/D 对管壁各测点温度的影响

Fig. 5 Influence of the tube diameter d/D on the tubewall temperatures at various measuring points

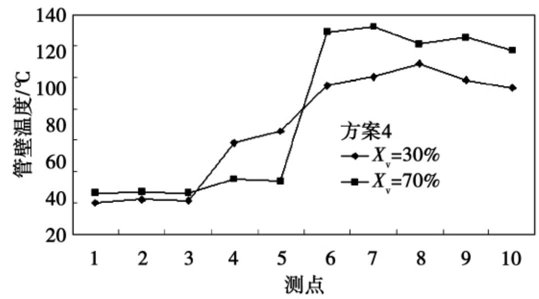

图 6　充液率 x_v 对管壁各测点温度的影响

Fig. 6 Influence of the liquid filling rate x_v on the tubewall temperatures at various measuring points

2.1.2　冷热端均温和传热温差

图 7 表明,定加热功率下,冷却水流量对热管冷热段均温和传热温差影响较小; 增加倾角,可使热段均温和传热温差降低,尤其是倾角大于 60°时,但对冷段均温影响很小; 增大管径,对冷段均温没有影响,但会使热段均温和传热温差明显降低; 30% 充液率管的冷段均温明显高于 70% 充液率管,而热段均温明显低于 70% 管,使传热温差也明显低于 70% 管。

2.1.3　传热热阻

图 8 表明,定加热功率下,中间冷却流量(70 L/h) 的管内传热热阻最小; 增加热管放置倾角,可降低传热热阻,尤其在倾角大于 60°时,90°热管的传热热阻最小; 增加管径可大幅降低传热热阻; 大充液率管(70%) 的传热热阻明显高于小充液率管

(30%)。

2.1.4　温度振幅及其波动

图 9 显示,定加热功率下,水冷却方式热管的冷端温度振幅小于热端振幅,其中,冷却水流量和倾角对冷热端振幅影响较小,而管径和充液率对振幅影响较大。增加管径和较小充液率都会使冷热端振幅降低,且热端振幅下降程度较冷端振幅的下降幅度大。

图 10 显示了基准测试 2 和另外 3 种温度振荡曲线较特殊的冷热段测点的壁温随时间的振荡曲线图。

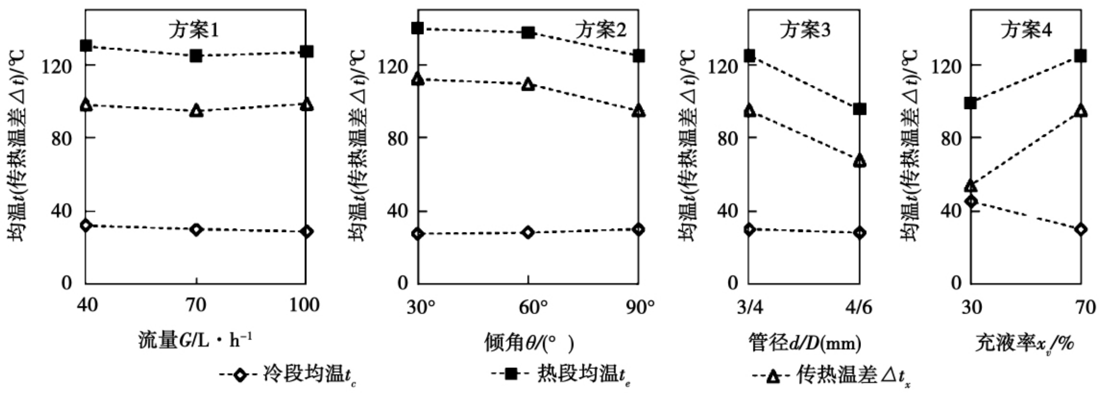

图 7　各因素对冷热段均温和传热温差的影响

Fig. 7 Influence of various factors on the mean temperature in the cold and hot sections and the heat conduction temperature difference

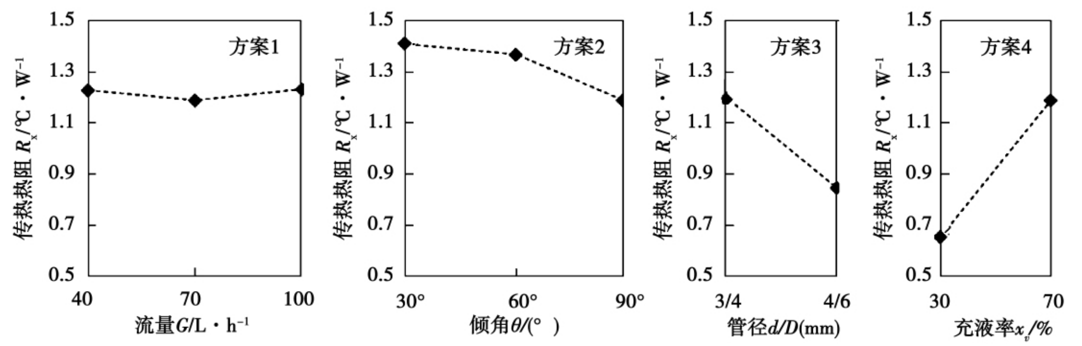

图 8　各因素对传热热阻的影响

Fig. 8 Influence of various factors on the heat conduction resistance

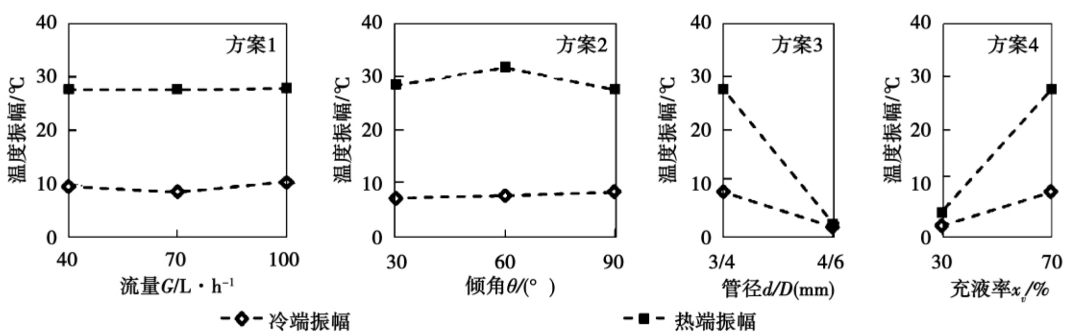

图 9　各因素对温度振幅的影响

Fig. 9 Influence of various factors on the temperature variation ranges

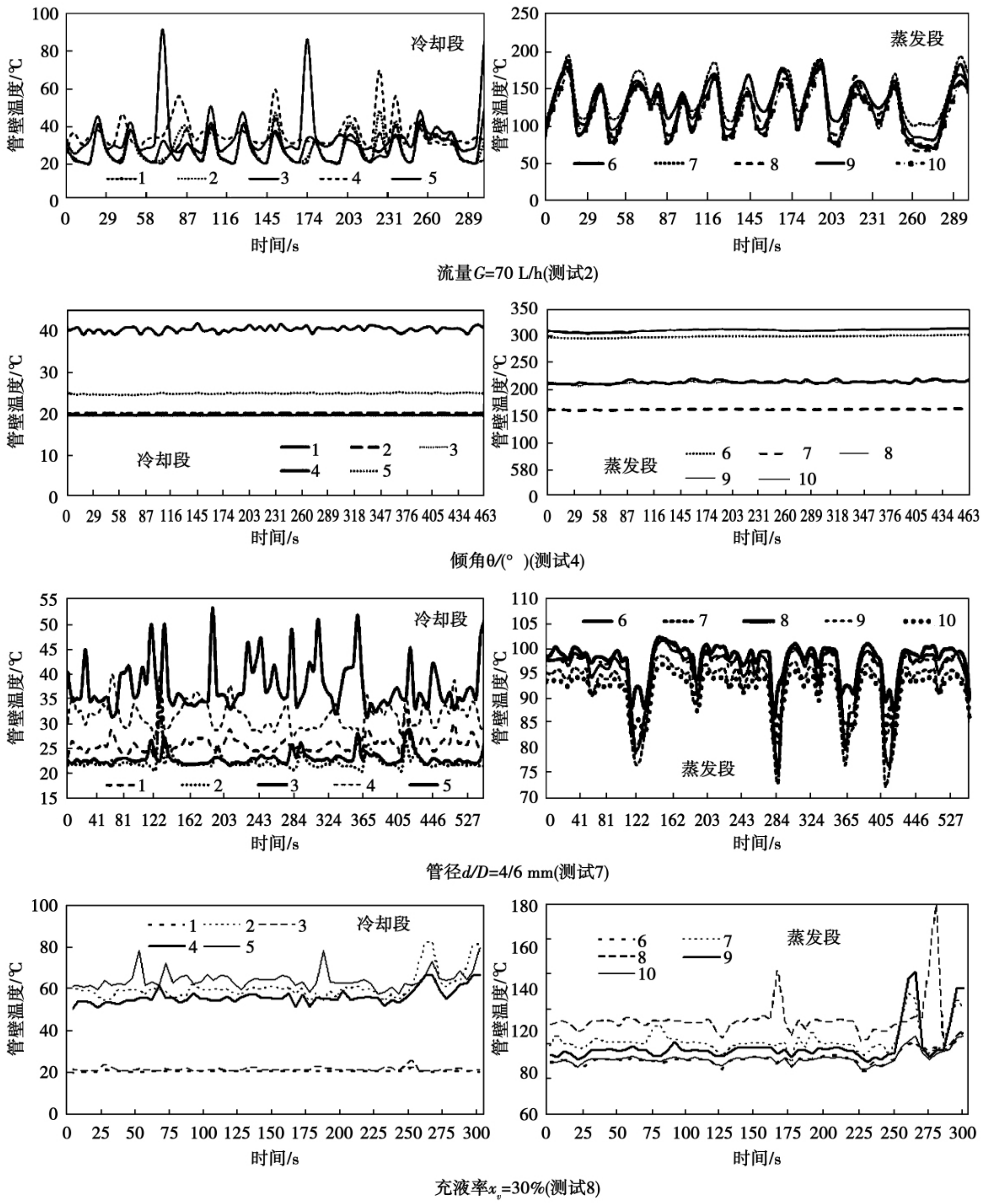

图 10　热管冷热段 10 个测点温度的波动曲线

Fig. 10 Curves showing the temperature fluctuation of the heat tube cold and hot section at 10 measuring points

从图 10 中的 4 张冷热段温度波动曲线中可看到,基准条件热管(测试 2) 的温度波动曲线呈较均匀的大幅锯齿状,且蒸发段 5 个测点的曲线基本重合,冷凝段 5 个测点的温度振幅有一定差别。测试 4 即热管在 0°倾角时,壁温基本无波动出现,说明热管没有启动。测试 7 即管径为 4/6mm 热管的壁温波动呈现“W”或“M”型,大幅振荡中间夹带小幅振荡。测试 8 即充液率为 30% 的热管壁温波动较小。

2.2　结果分析

图 8 ~ 图 10 显示,测试号为 1、2、3、5、6 号管的冷热段振幅较接近,温度波动呈现大幅度均匀锯齿状,热阻集中在 1 ~ 1.5 ℃/W 之间,说明当单回路热管倾角 $\theta \geq 30°$ 时,定加热功率下冷却水流量的改变对管内工质的振荡和传热热阻影响不大。后期的

变功率实验研究发现,大幅锯齿状振荡是出现在热管加热功率相对较低的情况,传热性能没达到最佳状态,若增加加热功率,它们的传热热阻会减小,传热性能会改善。

4 号测试(0°倾角)管内无振荡,传热热阻最大,为 2.68 ℃/W,说明水平放置的热管的传热只能靠管壁导热来完成,此结果与文献[2]显示的单回路振荡热管的实验结果一致。在文献[3~7]中,当热管弯数足够多时,热管在 0°倾角时也会出现管内工质的振荡,说明管弯数对热管振荡有很大影响。当热管弯数较少时,增加倾角可增大各平行管内非均匀分布的汽液塞的重力分量,导致不平衡势差增大,使管内工质扰动性增强,同时可促进上面冷凝段工质的回流,从而增强管内工质的振荡特性和启动。

图 9~图 10 中显示管径为 4/6 mm 热管的温度振幅和振荡频率明显小于 3/4 mm 管,振荡呈现“M”型,说明增加管径,管内工质的振荡性能下降,但在相同传热功率下,其热阻却明显低于 3/4 mm 管,如图 8 所示。研究认为,增加管径,相同充液率下,工质质量增加,同一驱动力下的振荡幅度和频率都会减弱,但管径增大也会使管内工质流动阻力下降,消弱了质量增加对振荡产生的影响;整体振荡减弱可认为工质振荡流速降低;另外,管径增大,管横截面积成平方倍增大,当横截面积的增加幅度大于流速的下降幅度时,意味着管内工质质量流速增加,在相同传热功率下,管内传热温差降低,对应的传热热阻减小。此结果说明在允许的直径范围内,增大管径有助于降低传热热阻。

图 9 显示,30% 充液率管的温度振幅明显小于 70% 管,且传热温差和传热热阻也明显低于 70% 管,但不能说明充液率越小,传热性能越好。但一些文献表明[8~11],充液率在 50% ~60% 之间时,传热性能最佳。本实验由于 50% 充液率管出现问题,所以没有 50% 管的数据。根据定传热功率下,循环流速、充液率、传热温差组成的传热量方程分析,30% 管的工质流速将近为 70% 管流速的 4 倍,说明管内工质较少时,传递相同热量,管内工质流速要比工质较多的管内流速大许多;同时结论显示,30% 充液率管的传热性能明显优于 70% 充液率管。

总之,80 W 传热功率下,4/6 mm 管径热管和 30% 充液率管的平均温度振幅在 2~4 ℃,热管传热热阻 0.8 ℃/W 左右,明显小于基准管(测试 2)的温度振幅和热阻。说明管内工质小而均匀的振荡,其传热性能明显优于大幅锯齿状的传热性能。

3　结　论

通过对定加热功率下单回路脉动热管水冷却条件下不同因素对热管传热性能影响的对比实验研究,得到以下结论:

(1) 水平放置的单回路脉动热管无法启动,30° 及以上倾角的热管有明显振荡。定加热功率下,增加倾角可改善热管的传热性能,但对管内工质的振荡幅度影响较小,90° 热管的传热性能优于其它倾角。

(2) 定加热功率下,冷却水流量存在最佳值,过大和过小都会降低热管的传热性能,增加管内传热热阻。

(3) 在振荡热管允许范围内,增大管径可提高热管传热性能。

(4) 在加热功率不够大时,30% 充液率管的传热性能明显优于 70% 充液率管。

(5) 小幅均匀振荡热管的传热性能优于大幅锯齿状振荡热管。

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新技术、新设计

简单循环余热回收可提高功率 25% ~40%

据《Gas Turbine World》2010 年年册报道,提高功率的联合循环废热回收通常对于简单循环电力设施和工业燃气轮机动力装置。

但是,对燃气轮机用于管线运行的情况不同。大多数管线运营天然气压缩机站一般建造在边远和无人居住的地区,这些地区常常不容易取水并且经常有很大的负荷变化。

鉴于上述情况,简单循环燃气轮机天然气泵送装置很少采用水蒸汽联合循环。

最近,闭路有机兰金循环废热回收装置正越来越受关注,在不需要燃烧更多燃料的情况下,该装置可以提高 40% 的功率。

现在已利用一系列这种小型热回收动力装置对沿主输气管网安装的 RB211 燃气轮机驱动压缩机站进行升级改造。改装的 9 台机组已在天然气管线上投入运行,另一台机组正处在建造阶段。

在连续满负荷输出功率下,每台 29 840 kW RB211 燃气轮机约产生 94.8 kg/s 排气量,温度为 492℃。

该热排气用来蒸发有机不结冰的工作流体,以便驱动涡轮发电机发电,最后通过空冷冷凝器回收并利用。

由 Ormat 供应的电力生产系统使用增压有机蒸汽驱动简化的 1 800 r/min 涡轮发电机,在燃气轮机 50% 部分负荷下,生产 3.5 MW 功率,在 100% 满负荷下生产 7.5 MW 功率。

(吉桂明　摘译)

inlet and outlet temperature differences of the cold and hot fluid in both single-side and diagonal flow will invariably decrease. Furthermore, such a decreasing tendency of the diagonal flow is bigger than that of the single-side flow while the friction factor *f* and heat transfer factor *j* will gradually decrease. The flow and heat transfer characteristics of a single-side flow is superior to that of a diagonal flow. **Key words**: single-side flow, diagonal flow, numerical simulation, flow, heat exchange

管程组合转子传热及阻力特性的实验研究 = **Experimental Study of the Heat Transfer and Resistance Characteristics of a Tube-side Combined Rotor** [刊,汉] YANG Wei-min, HAN Chong-gang, ZHANG Zhen (Beijing University of Chemical Technology, Beijing, China, Post Code: 100029), LI Feng-xiang (Patent Bureau, State Intellectural Property Office of PRC, China, Post Code: 100191) //Journal of Engineering for Thermal Energy & Power. -2011, 26(6). -681~686

Tube-side combined rotor intensification technology has its functions to intensify heat transfer and self clean. With the help of the test means and oil and water serving as the working medium respectively in the tube side, studied were the heat transfer and resistance characteristics of a tube-side combined rotor. In the meantime, the influence of the self structural parameters of the rotor under discussion on its heat transfer and resistance characteristics was compared and analyzed. The analytic results show that in the laminar flow and transitional zone where $Re = 500-8000$, to increase the spiral angle of the rotor can remarkably intensify the heat transfer. However, in the torrent turbulent flow zone where $Re = 10^4 \sim 10^5$, to increase the outer diameter of the rotor can obviously intensify the heat transfer, thus, laying a foundation for application of rotor combination type heat transfer intensification devices in various industries. **Key words**: tube-side combined rotor, intensified heat transfer, resistance, structural parameter

单回路紫铜—水脉动热管传热性能的实验研究 = **Experimental Study of the Heat Transfer Performance of a Single-loop Copper-water Pulsation Heat Pipe** [刊,汉] SU Lei, ZHANG Hong, DING Lei-jiang, et al (College of Energy Source, Nanjing Institute of Technology, Nanjing, China, Post Code: 210009) // Journal of Engineering for Thermal Energy & Power. -2011, 26(6). -687~693

Experimentally studied was the law governing the influence of four factors, namely, cooling water flow rate, inclination angle, tube diameter and liquid filling rate, on the heat transfer performance of a single-loop copper-water pulsation heat pipe, including its tube wall temperature at measuring points, mean temperature in the cold and hot section, heat transfer temperature difference, heat transfer resistance and temperature fluctuation. As a result, some measures for enhancing the heat transfer performance were obtained. The research results show that the single-loop pulsation heat pipe arranged horizontally can not be started up with any possible methods and at an inclination angle of over 30 degrees, oscillation may be produced inside the pipe and to increase the inclination angle can lower the heat transfer resistance. At a given thermal power, there exists an optimum value of the cooling water flow rate and

if excessively higher or lower than it, the heat transfer resistance will always increase. Within the limits of the tube diameter permited by the pulsation heat pipe, to increase the tube diameter can greatly reduce the heat transfer resistance. At a same heat-transfer power, the heat transfer resistance of a heat pipe having a liquid filling rate of 30% will be obviously lower than that having a liquid filling rate of 70%. The heat transfer performance resulted from a small and uniform wall temperature fluctuation is superior to that from a big and serration wall temperature fluctuation. **Key words**: single-loop pulsation heat pipe, liquid filling rate, tube diameter, heat transfer performance

水平管降膜蒸发器的全三维数值模拟 = **Full-three-dimensional Numerical Study of a Horizonal-tube Falling-film Evaporator** [刊,汉] HOU Hao, BI Qin-cheng, ZHANG Xiao-lan (National Key Laboratory on Multiphase Flows in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. - 2011, 26(6). -694 ~699

In the light of the flow and heat transfer problems existing in the operation and optimized design of a horizontal-tube falling-film evaporator, established was an entity three-diemnsional distributed parameter model for the evaporator and studied in depth were such characteristics as seawater flow field and temperature field etc. inside the evaporator by using a numerical simulation method. In this connection, the detailed information showing the distribution of the corresponding thermal parameters was acquired, visually depicting the operation process, complex flow and heat exchange phenomena inside the evaporator. Through a comparison of the numerical solutions with the actual values, the model in quesiton was verified. The calculation results show that the total heat transfer coefficient in the first and second steam inlet zone of the tube side is the biggest and the seawater displays the microscopic law of the sprinkling density in "the upper portion being higher than that in the lower" and the salinity in the "upper portion being smaller than that in the lower". When the seawater supply flow rate changes in a range of 280 - 370 t/h, it has a big influence on the temperature difference of the secodnary steam and heating steam but has no significant influence on the production capacity of the secondary steam, indicating that the deviation of the seawater flow rate from its design value may result in an abnormal operation of the whole seawater desalination system. **Key words**: horizonal-tube falling-film evaporator, distributed parameter model, flow and heat exchange, numerical simulation

船用真空海水淡化装置液-汽引射器的数值模拟及试验研究 = **Numerical Simulation and Experimental Study of the Liquid-steam Ejector of a Marine Vacuum Seawater Desalination Device** [刊,汉] WANG Xiao-juan, ZHANG Bo (Navigation College, Northwest Polytechnic University, Xi'an, China, Post Code: 710072), GAO Chun-lin (Troop 91287 of PLA, Shanghai, China, Post Code: 200833), YANG Dong (Naval Aviation Military Representative Office Resident in Xi'an Region, Xi'an, China, Post Code: 710021) //Journal of Engineering for Thermal Energy & Power. - 2011, 26(6). -700 ~704

According to the one-dimensional ejection characteristic equation, predicted were the optimum ejection parameters of a marine vacuum seawater desalination device, then by using the numerical calculation and test methods, studied