

# 制冷剂 R-134a 在螺旋环形通道 内凝结换热的实验研究

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**摘 要:** 制冷剂 R-134a 在螺旋管内的凝结换热和压力降特性数据对于制冷空调和热泵等系统的设计改造及运行都具有重要的理论意义和工程应用价值。本文对 R-134a 在螺旋环形通道内的凝结换热和压力降特性进行了实验研究, 得到了平均的凝结换热系数和压力降特性的实验数据, 并与文献报导的 R-134a 在直管和螺旋管内凝结换热的实验结果进行了比较, 所得实验数据可望为新型螺旋管换热器的开发设计和工程应用提供参考数据。

**关 键 词:** 凝结换热; 螺旋环形通道; 替代制冷剂; 压力降; 相变传热

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## 1 引 言

世界各国普遍关注的全球性气候变化要求在制冷、空调和热泵等领域采用对环境无污染的替代制冷剂, 而 R-134a 被认为是 R-12 的理想替代物。由于 R-134a 的热物性与原有工质的不同, 因此, R-134a 凝结换热和压力降特性对于新设备与系统的设计开发和原有设备与系统的技术改造都具有重要的应用价值<sup>[1]</sup>。由于螺旋管换热器具有结构紧凑、传热强度高和制作简单等优点, 因而采用 R-134a 为制冷剂的螺旋管换热器在制冷、空调和热泵等系统中具有重要的应用前景<sup>[2~3]</sup>。

目前, 国内外对 R-134a 在管内凝结换热和压力降特性的研究主要对直管(束)和各种结构的强化换热管进行的<sup>[4~9]</sup>, 而对 R-134a 在螺旋管内的凝结换热的研究则很少。Uddin 等人对 R-134a 在螺旋管中的局部凝结换热系数及其与螺旋管的几何结构参数的关系进行了实验研究<sup>[10]</sup>。Zaki 和 Kang 等人报道了 R-134a 在螺旋管中凝结换热的实验结果<sup>[11~12]</sup>。

Han 等人实验研究了蒸汽过热度对 R-134a 在螺旋管中凝结换热特性的影响<sup>[13]</sup>。已有研究表明, 螺旋管中的离心力和二次回流使 R-134a 在螺旋管中的凝结换热得到了一定程度的强化。值得指出的是, 上述研究均是对 R-134a 在螺旋管内的凝结换热过程进行的<sup>[10~13]</sup>, 目前尚未见到有关 R-134a 在螺旋环形管道内凝结换热的报道。因此, 本文对 R-134a 在螺旋环形通道内的凝结换热和压力降特性进行实验研究, 得到了平均的凝结换热系数和压力降特性数据, 并与文献报导的 R-134a 在螺旋管和直管内凝结换热和压力降的实验结果进行了比较。

## 2 实验装置和方法

所采用的实验装置和相应的参数测点布置如图 1 所示。实验装置主要由制冷剂环路、冷却水环路和有关的测试装置及数据采集系统等组成。制冷剂 R-134a 与冷却水分别在螺旋环形通道和螺旋管内逆向流动。值得指出的是, 在文献<sup>[10~13]</sup>的有关实验研究中, R-134a 与冷却水分别是在螺旋管内和螺旋环形通道内逆向流动, 其流动布置与本文实验研究的正好相反。R-134a 由驱替泵从储液罐送到加热锅炉, 过冷制冷剂由加热锅炉变成饱和蒸汽, 再由过热器加热成具有一定过热度的过热蒸汽, 过热蒸汽由流量计测量其流量后进入螺旋管实验段的环形通道内。凝结后的制冷剂经辅助冷凝器进一步冷却后, 送到储液罐而形成一个循环。在实验系统中通过 SCR 精密温度控制系统确保实验中制冷剂加热温度的准确可靠性。实验系统中采用驱替泵而不是采用压缩机的目的主要是为了避免制冷剂环路受压缩机润滑油的影响。冷却水环路主要由恒温水

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浴、冷却水泵、温度控制系统、流量计和调节阀等组成。为了观察 R-134a 在螺旋环形通道内的冷凝过程, 在螺旋环形实验管段进口和辅助冷凝器的进口分别布置了两个玻璃观察窗口。实验段管路系统由玻璃纤维绝缘材料保温。

如图 1 所示, 在实验系统中的不同位置分别布置了测量制冷剂和冷却水温度和压力等参数的测点。实验段制冷剂侧的冷凝压力降是采用高精度的差压计测量的, 实验段中制冷剂和冷却水的进出口温度分别用铠装热电偶测量。测量仪表的输出信号均由 National Instruments (NI) 公司的数据采集系统采集和存储。

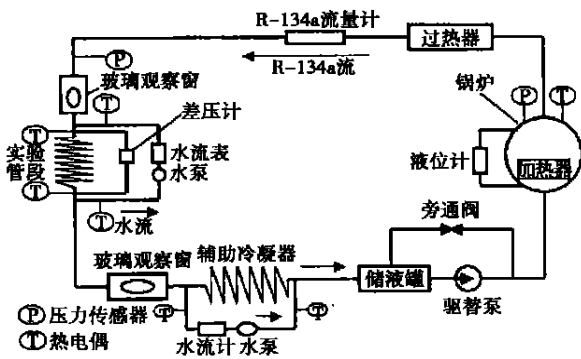


图 1 实验系统示意图

图 2 给出了实验所采用的螺旋环形实验段的结构示意图。螺旋环形管实验段是由美国 Parker Instrumentation 公司提供的, 它的内外管均是由铜管组成, 其中内管的内外径分别是 9.4 mm 和 12.7 mm, 而外管的内径是 21.2 mm, 螺旋管直径和节距分别是 34.9 mm 和 177.8 mm, 螺旋管的总圈数是 10。

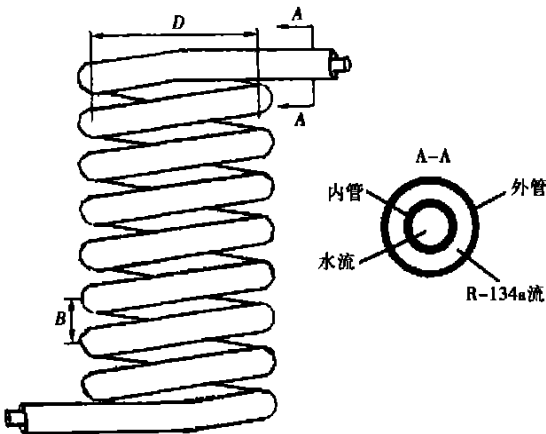


图 2 实验段结构示意图

在全面检查和排除了实验系统的泄漏问题之后, 用真空泵将制冷剂环路抽真空, 并将 R-134a 充到制冷剂环路中。实验用的热电偶在安装前后均经过了严格的校验, 压力表、差压计和流量计等也进行了仔细的校验。

### 3 实验数据整理方法

实验数据的整理是基于制冷剂的放热量与冷却水的吸热量之间的能量平衡进行的。制冷剂 R-134a 在冷凝过程中传递给冷却水的热量  $Q$  可由下述方程确定:

$$Q = F_w \rho_w c_{pw} (T_{w, out} - T_{w, in}) \quad (1)$$

其中:  $F_w$ 、 $\rho_w$ 、 $c_{pw}$ 、 $T_{w, in}$  和  $T_{w, out}$  分别是冷却水的体积流量、密度、比热和进出口温度。

根据牛顿冷却定律, 螺旋管实验段(螺旋管冷凝器)总的换热量可由下式求得:

$$Q = AU_o \Delta T = F_w \rho_w c_{pw} (T_{w, out} - T_{w, in}) \quad (2)$$

因此, 螺旋管冷凝器的总的换热系数为:

$$U_o = \frac{F_w \rho_w c_{pw} (T_{w, out} - T_{w, in})}{A \Delta T_{LMTD}} \quad (3)$$

其中:  $U_o$ 、 $A$  和  $\Delta T_{LMTD}$  分别是总的换热系数、换热面积和对数平均温差。

而对数平均温差可由下式确定:

$$\Delta T_{LMTD} = \frac{(T_{f, out} - T_{w, in}) - (T_{f, in} - T_{w, out})}{\ln[(T_{f, out} - T_{w, in}) / (T_{f, in} - T_{w, out})]} \quad (4)$$

其中:  $T_{f, in}$  和  $T_{f, out}$  分别是在实验段中制冷剂的进出口温度。

在假定污垢热阻可以忽略不计的情况下(因为实验所用螺旋管实验段均经过仔细的清洗), 根据总的换热系数可以得到制冷剂的冷凝换热系数  $h_f$ :

$$h_f = \frac{1}{\frac{1}{U_o} - \frac{1}{h_w} - R_t} \quad (5)$$

其中:  $R_t$  和  $h_w$  分别表示螺旋管内管壁的热阻和水侧的对流换热系数。

水侧的对流换热系数是根据修正的威尔逊方法实验确定的<sup>[14~15]</sup>。根据得到的威尔逊实验数据, 通过回归方法得到了在不同水流速和温度条件下确定水侧换热系数的实验关联式。

实验过程中, 通过校核制冷剂的放热量和冷却水的吸热量之间的热平衡来判断系统是否达到了稳态条件。本文发展了一个计算机子程序, 该程序通

过检测制冷剂和冷却水测点的温度变化可以方便地判断实验系统是否达到了稳态条件。为了考虑冷凝过程中压力降对凝结特性的影响, 制冷剂 R-134a 的平均饱和温度是由实验段的平均饱和压力确定的。制冷剂的热物性参数是由实验段制冷剂平均饱和温度计算的, 而水的热物性参数是用实验段冷却水进出口的平均温度确定的。

为了减少各种扰动因素对实验结果的影响, 本文在数据处理过程中采取了数字滤波等数据处理方法<sup>[6]</sup>。对于温度测量信号采取了多次重复测量求其平均值的方法。由于实验中制冷剂在实验段凝结过程中的压力降波动较大, 因此, 对于压力降采取较多次数测量, 并在去掉多次测量数据中的最大值和最小值后再求剩余测量值的平均值。由于所采用的测量制冷剂 R-134a 流量的流量计本身已配有测量数据处理的完整程序, 因此, 可以直接采用制冷剂流量的实验数据。实验结果表明, 上述措施是切实可行的, 可以满足本文实验研究的要求。

#### 4 实验数据的不确定度分析

根据文献[17]中Moffat的实验误差传递分析方法, 对实验数据整理方法进行了实验数据的不确定度分析。实验中直接测量温度、压力(差)和流量等。根据测量仪器的产品说明书和校验数据, 制冷剂流量测量的不确定度是±1%, 冷却水体积流量测量的不确定度是±2%, 温差测量的不确定度是±0.2℃, 总的凝结换热系数、冷却水侧的对流换热系数和制冷剂侧的平均凝结换热系数的不确定度分别是±9.46%、±5.0%和±15.5%, 冷却水侧 Reynolds 数的不确定度是±2.5%。

根据上面的实验数据整理方法, 设计了基于FORTRAN语言的计算机程序, 数据处理过程可以很方便地由该程序实现。

#### 5 实验结果与分析

对制冷剂 R-134a 分别在 3 个不同的饱和温度下(35、40 和 46℃)的凝结换热和压力降特性进行了实验研究, 实验中制冷剂的质量流量变化范围是 100~420 kg/(m<sup>2</sup>s)。

图 3 给出了实验得到的螺旋管实验段的平均热流  $q$  与制冷剂质量流量  $m_f$  之间的关系, 其中热流和

制冷剂的质量流量分别是:

$$q = \frac{Q}{\pi dL}, m_f = \frac{F_f \rho_f}{(\pi/4)(d_{in}^2 - d_{out}^2)} \quad (6)$$

式中:  $d$  和  $L$  分别是螺旋管内管的平均直径和长度;  $Q$  是总的凝结热流;  $F_f$  和  $\rho_f$  分别是制冷剂的体积流量和密度,  $d_{in}$  和  $d_{out}$  分别是螺旋管实验段外管的内径和内管的外径。

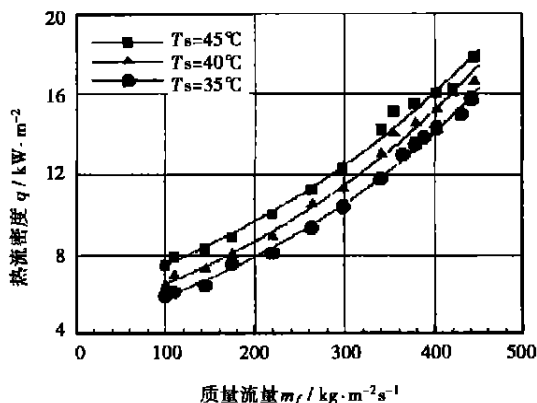


图 3 平均热流与 R-134a 质量流量间的关系

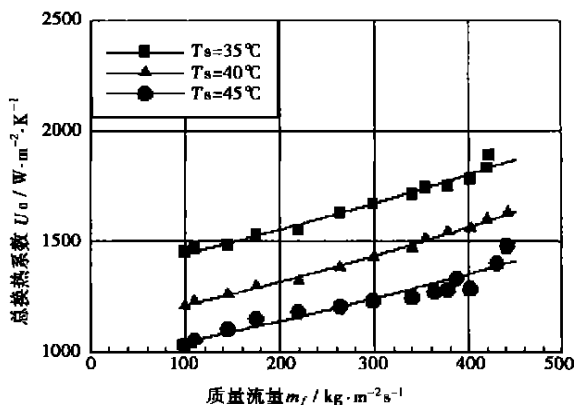


图 4 总换热系数与 R-134a 质量流量间的关系

由图 3 可知, 凝结过程的平均热流随着制冷剂质量流量的增加而增大。此外, R-134a 的饱和温度变化对平均凝结热流具有明显的影响。文献[10~12]对 R-134a 在螺旋管内凝结换热的研究也得到了类似的变化趋势。

图 4 给出了螺旋管冷凝器的总换热系数与制冷剂质量流量之间的关系。由图 4 可以看出, 螺旋管冷凝器的总换热系数随着制冷剂质量流量的增加而增大, 当制冷剂流量增加 3 倍时, 总换热系数增加了约 40%。因此, 制冷剂质量流量的变化对总换热系

数具有明显的影响。此外, 制冷剂的饱和温度变化对总换热系数的影响也可以从图 4 中清楚地看出。显然饱和温度变化对 R-134a 在螺旋环形通道内总换热系数的影响趋势与文献中报道的 R-134a 在直管和强化换热管内的凝结换热过程具有类似的变化趋势。

实验得到的制冷剂侧平均凝结换热系数与制冷剂质量流量之间的变化关系如图 5 所示。与总换热系数的变化趋势类似, 制冷剂侧的平均凝结换热系数也是随着制冷剂质量流量的增加而增大, 这与文献 [4~5, 7, 11~12] 中报道的 R-134a 在直管和螺旋管内的凝结换热系数的变化趋势也是相似的。

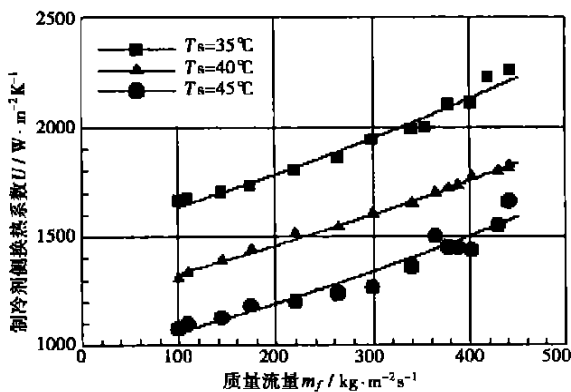


图 5 制冷剂侧凝结换热系数与 R-134a 质量流量间的关系

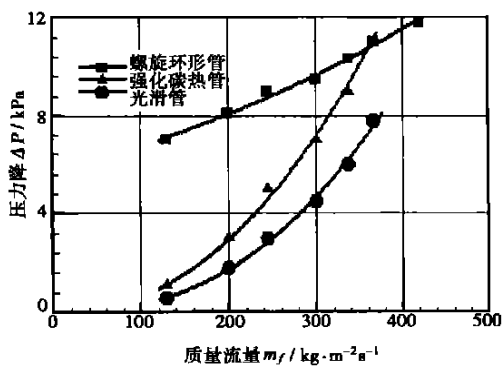


图 6 平均压力降与 R-134a 质量流量间的关系

图 6 给出了 R-134a 在螺旋环形通道内凝结过程的平均压力降与质量流量间的关系。显然, 螺旋环形通道内凝结过程的压力降随着制冷剂质量流量的增加而增大。由图 6 可以看出, 在相同的质量流量条件下, R-134a 在螺旋环形通道内凝结过程的平

均压力降比文献 [4] 中给出的直管和强化换热管的压力降要高。此外, R-134a 质量流量的变化对其在直管和强化换热管内凝结压力降的影响比在螺旋环形通道内的更明显。值得指出的是, 图 6 给出的压力降数据的比较只能是定性的, 因为除了实验段的几何参数不同外, 实验研究的条件也不完全相同。

由于到目前为止, 文献中尚未见到有关 R-134a 在螺旋环形管中凝结换热过程的研究报道, 因此尚无法将本文的实验数据与其它研究结果进行比较。

## 6 结束语

本文对制冷剂 R-134a 在螺旋环形通道内的凝结换热和压力降特性进行了实验研究。在制冷剂流量从  $100 \sim 420 \text{ kg}/(\text{m}^2\text{s})$  的变化范围内, 得到了制冷剂在 3 个不同饱和温度 (35, 40 和  $46^\circ\text{C}$ ) 下的平均凝结换热系数和压力降特性数据。实验结果表明, 总的换热系数、制冷剂侧的凝结换热系数和平均的压力降均随着制冷剂质量流量的增加而增大, 制冷剂的饱和温度对凝结换热过程具有明显的影响。此外, 本文将螺旋环形通道内的实验数据与文献中报道的 R-134a 在直管和螺旋管内的凝结换热和压力降特性进行了分析比较。本文所报道的凝结换热和压力降特性的实验数据可望为新型螺旋管换热器的设计和运行提供参考依据。

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由于含有纳米颗粒, 导热系数提高, 减小了液膜的热阻。另一方面, 纳米颗粒的惯性力和布朗运动增加了冷凝段液膜的扰动, 破坏了冷凝段的热边界层, 从而强化了冷凝段的传热。综上可知, 在加入纳米颗粒后, 由于蒸发段和冷凝段的传热都得以加强, 所以两相闭式热虹吸管的传热比不加纳米颗粒的热管有了很大的提高。

## 5 结 论

(1) 提出了一种新的提高热传递的方法—在以水为工作液体的热虹吸管中加入一定数量的纳米颗粒, 并且实验研究了加热段的热传递特性, 这种新的热管能够简单、方便地应用于工程技术中。

(2) 与普通热管相比较, 加热段的换热系数提高了 47%~96%, 轴相热流率提高了 7.6%~15%, 具有很好的启动特性, 且管壁温度降低了 6~8 °C。

(3) 热虹吸管的换热系数随纳米颗粒粒径的减小而增大, 开始阶段随纳米颗粒加入量的增加有所增加, 当超过一定份额时热虹吸管换热性能减弱。

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nozzle with fine adaptability to incidence and a good transonic performance represents a key technology of variable-geometry power turbine design for a naval gas turbine. In view of this, on the basis of the numerical calculation results, the authors' analysis has been focused on the aerodynamic performance and the flow field structure of the variable-area nozzle stage. **Key words:** naval gas turbine, variable area nozzle, variable-geometry power turbine, three-dimensional viscous flow field, numerical investigation

两套后部加载叶栅的对比实验研究 = **Contrast Experimental Study of Two Kinds of Rear-loaded Cascades** [刊, 汉] / YUE Guo-qiang, HAN Wan-jin, LU Wen-cai (College of Energy Science & Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), LI Dian-xi (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). — 125 ~ 129

To investigate the impact of blade front-edge diameter and load distribution on the aerodynamic performance of rear-loaded cascades, a contrast blow-down test was conducted of two sets of rear-loaded cascades with different front-edge diameters and load distribution. Detailed measurements were taken of the flow field parameters and surface static pressure at the following incidences:  $0^\circ$ ,  $+20^\circ$ ,  $-20^\circ$ . The results of the investigation indicate that through a proper selection of the front and rear edge diameter and a rational matching of outlet inverse-pressure stage length and inverse pressure gradient magnitudes it is possible to effectively reduce the secondary flow losses of the cascades and enhance the adaptability of cascades to incidence variation, thus resulting in a more uniform distribution of outlet flow-field aerodynamic parameters along the blade height. **Key words:** rear loading, experimental investigation, incidence, cascade

平板滞止区内饱和液体喷流沸腾的临界热流密度 = **Critical Heat flux Density of the Jet Flow Boiling of a Saturated Liquid in a Flat-plate Stagnation Zone** [刊, 汉] / QIU Yu-hao, LIU Zhen-hua (College of Mechanical & Power Engineering under the Shanghai Jiaotong University, Shanghai, China. Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). — 130 ~ 133

A systematic steady-state experimental study was conducted with respect to the critical heat-flux density of a round jet-flow impingement boiling of a saturated liquid in a high-temperature flat-plate stagnation zone. Investigated was the influence of the various system conditions, such as different liquids, flow velocities and jet flow diameter, etc. on the critical heat-flux density of the jet-flow boiling. A semi-theoretical and semi-empiric equation was established for forecasting the critical heat-flux density. The basic form of the equation was obtained by adopting available former research results. The coefficients of the equation were derived by a fitting of the experimental data of the present study. The study results indicate that the critical flow-flux density of the saturated fluid jet-flow impingement boiling depends on the physical properties of the liquid, stagnation impingement speed and jet flow diameter. By using the semi-theoretical and semi-empirical formula obtained as a result of the present study it is possible in a extensive range of tests accurately predict the critical heat-flux density of the jet-flow boiling. **Key words:** jet flow, boiling, critical heat-flux density

制冷剂 R-134a 在螺旋环形通道内凝结换热的实验研究 = **Experimental Investigation of the Condensation Heat Exchange of Refrigerant R-134a in a Spiral Ring-shaped Channel** [刊, 汉] / HAN Ji-tian, SU Guo-ping (College of Energy & Power Engineering under the Shandong University, Jinan, China, Post Code: 250061) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). — 134 ~ 137, 141

The role played by refrigerant R-134a in the condensation heat exchange in spiral tubes and its pressure-drop characteris-

tics data are of major theoretical significance and have a high practical value in engineering applications so far as the design modification and operation of such systems as refrigeration air conditioning units and heat pumps, etc. are concerned. The authors have carried out an experimental study regarding the condensation heat exchange and pressure-drop characteristics of the refrigerant R-134a in a spiral ring-shaped channel. As a result, experimental data, such as average condensation heat exchange factor and pressure-drop characteristics were obtained, which were compared with the test results of R-134a as reported in available literature concerning its condensation heat exchange in straight pipes and spiral pipes. The experimental data thus obtained can serve as a reference during the development, design and application of new types of spiral tube heat exchangers. **Key words:** condensation heat exchange, spiral ring-shaped channel, replacement refrigerant, pressure drop, phase-transition heat exchange

纳米颗粒强化热虹吸管传热特性的实验研究 = **Experimental Study of the Intensified Heat Transfer Characteristics of a Thermosiphon Through the Addition of Nanoparticles** [刊, 汉] / PENG Yu-hui, HUANG Su-yi (Institute of Energy and Power Engineering under the Huazhong University of Science & Technology, Wuhan, China, Post Code: 430074), HUANG Kun-jian (Hunan Provincial Key Laboratory of High-efficiency Heat Exchange Technology and Equipment, Changsha, China, Post Code: 410000) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). — 138 ~ 141

With the rapid development of nanometer technology some research workers have gradually applied this high and new technology to the traditional realm of thermal energy and power. The authors have from a theoretical and experimental viewpoint studied the working characteristics of the evaporation section of a thermosiphon, to which nanoparticles have been added. The results of the study indicate that as compared with conventional heat pipes this type of innovative heat pipes features excellent start-up characteristics and low pipe-wall temperature with heat exchange factor being enhanced by 47% ~ 96% and axial heat flux rate by 7.6% ~ 15%. In addition, their heat exchange performance will increase with the decrease in nanoparticle diameter, and will slightly increase with the addition of nanoparticles. However, when the added nanoparticles have exceeded a certain amount, the heat exchange performance will on the contrary experience a degradation. This innovative method can be applied in industrial units easily and simply. **Key words:** nanofluid, nanoparticles, intensified heat transfer, thermosiphon

垂直布置 B30 波槽管管外膜状凝结的实验研究 = **Experimental Investigation of the Tube-outside Film-shaped Condensation in a Vertically Installed B30 Corrugated Tube** [刊, 汉] / ZHAO Ri Ge-tu, HUANG Wei-tang, LIU Feng (Institute of Power & Nuclear Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(2). — 142 ~ 144, 157

Under the condition of condensation at a pressure slightly higher than the atmospheric one an experimental investigation was conducted of the tube-outside film-shaped condensation heat exchange in a vertically installed corrugated tube. The results of the investigation indicate that the vertically installed corrugated tube enjoys definite heat-transfer intensification effectiveness. Within the range of the experiments the overall heat transfer factor of an optimum corrugated tube is higher than that of a bare tube by 27% ~ 43%, while its resistance factor is about 2.94 ~ 3.48 times that of a bare tube. The heat transfer intensification effectiveness of a vertically installed tube is inferior to that of a horizontally installed one. Through a regressive analysis of the test data an experimental correlation formula was obtained for the following items of the vertical tube: the tube-inside convection heat exchange, the tube-outside condensation heat exchange and the resistance factor. **Key words:** vertical, intensified heat transfer, corrugated tube, film-shaped condensation