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管内加装波形板扰流件强化对流传热的试验研究

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摘　要：采用试验的方法，对装有波形板扰流件的管内高温烟气在小 Re 数条件下的对流传热及阻力特性进行了研究，并将试验结果分别与无波形板和相关经验公式进行了比较。研究结果表明：管内加装波形板扰流件后，可使高温烟气的对流传热性能得到明显强化，且随着 Re 数的增大，强化效果越好；波形板扰流件的对流传热强化率为1.6－3.5。根据试验结果总结出 $1\ 300 < Re < 3\ 500$ 时加装波形板扰流件后管内烟气的对流传热与管子阻力系数的关联式。

关　键　词：管内对流；雷诺数；波形板扰流件；强化传热

中图分类号：TK172　　**文献标识码**：A

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符号说明

Re——雷诺数
Pr——普朗特数
S、U——分别为波形板的波间距、波高，m
α——波形板的倾角，(°)
E——对流传热强化率
A——传热面积，m^2
h——传热系数，$W/(m^2 \cdot K)$
d——当量直径，m
$\triangle P$——阻力降，Pa
ζ——阻力系数
l——有效长度，m
ρ——气体密度，kg/m^3
v——气体流速，m/s
η——传热强化性能指标
下角标
c——有波形板扰流件
p——无波形板扰流件
0——无扰流件

引　言

小 Re 数条件下气体对流传热的强化历来是研究热点[1-3]。管内插入扰流件是一种有效的强化传热方式，尤其对强化小雷诺数 Re 气体或高黏度流体的传热更为有效[4-6]。波形板是扰流件的种类之一，可使速度边界层减薄，热边界层遭到破坏，从而强化传热。因此，用波形板扰流件强化小雷诺数 Re 下流体传热，具有十分重要的意义。

文献[7]用水作为工质进行了管内加装倒角尖锐形状波形板的对流传热强化研究，并根据试验结果总结出了 $2\ 000 < Re < 33\ 000$、$4 < Pr < 11$ 范围内的对流传热关联式；文献[8]试验研究表明，波形板通道内的对流传热性能是光管的3.5倍；文献[9]研究了波形板的几何参数对传热的影响，得出波形板的波节距、波高、倾角对强化传热起到重要的影响；文献[10]的研究指出，层流时波形板不能显著强化传热，湍流时波形板能够使流体更好地掺混，进而明显强化传热；文献[11]认为，波形板通道内流动状态分为层流、稳定再循环层流、不稳定再循环过渡流、旋涡过渡流、湍流等；文献[12]以空气为介质，研究了波形板倾角对对流传热的影响，波形板倾角从20°增加到70°，对流传热的努赛尔数 Nu 提高了80%；文献[13]的数值模拟研究表明，正弦状波形板强化传热的临界 Re 数为175－200，当雷诺数 Re 高于临界值时，波形板能有效强化传热；文献[14]对5种不同板型的波纹板进行了试验研究，认为V形波纹板的强化传热性能最佳。

综上，波形板能有效地强化传热，尤其对小雷诺数 Re 条件下的流体流动情况，且强化对流传热的程度与雷诺数 Re 有关。然而，有关波形板对高温气体强化传热的研究甚少，相关的对流传热关联式鲜见报道。本研究将对波形板应用于管内高温烟气进行研究，旨在为实际应用提供理论依据。

1　实验装置

试验装置如图1所示。通过燃烧液化石油气产

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生高温烟气,与室温冷空气混合成试验所需进口温度(温度反馈控制)条件下的混合烟气,混合后的烟气经过 90°弯头后,流经长为 600 mm 稳定段,然后自下而上进入试验段管内。试验段上升管的横截面如图 1 所示,外壁自然冷却。试验段的材质为 1Cr13,外管规格为 $\Phi 432 \times 6$ mm,内壁等间距地焊接有直翅片,翅厚 4 mm,翅高 50 mm。波形板包围的内筒规格为 $\Phi 312 \times 6$ mm ,单个波形板结构如图 2 所示,实物如图 3 所示,倾角 $\alpha = 90°$,无因次尺寸 $S/d = 0.5$,$U/d = 0.25$,其中 S 为波间距,U 为波高,d 为当量直径,单位为 m。试验段的有效高度为 1 720 mm。试验段外壁高度方向螺旋线形地焊接有 40 个 K 型热电偶。烟气的进、出口温度分别由布置在相应位置处的 2 个铠装 K 型热电偶测定。所有温度由数据采集仪读取。烟气流经试验段的压力降由 MAGRFHELI 微压差表测定。通过测定一定时间间隔内液化石油气的耗量,计算出烟气量,根据温度调控室反馈的温度计算出掺入的室温空气量,从而确定出进入试验段管内的混合烟气量。

试验前,所有的测温热电偶都进行了温度校正,混合烟气进口温度的测量误差为 0.16% ,烟气出口温度的测量误差为 0.5% 。根据文献 [5] 不确定度理论,试验段管壁温度的不确定度为 0.1% ,烟气流速的不确定度为 2% 。雷诺数 Re 的不确定度为 3.6% ,努赛尔数 Nu 的不确定度为 2.88% ,对流传热系数的不确定度为 4.16% 。

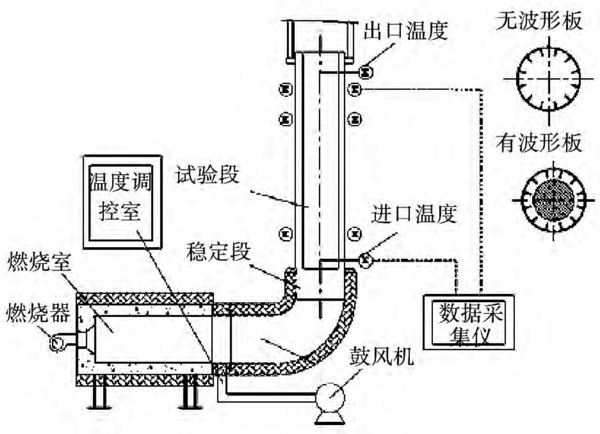

图 1　试验装置示意图

Fig. 1 The schematic diagram of experimental apparatus

图 2　波形板扰流件示意图

Fig. 2 The schematic diagram of corrugated plate disturbed flow component

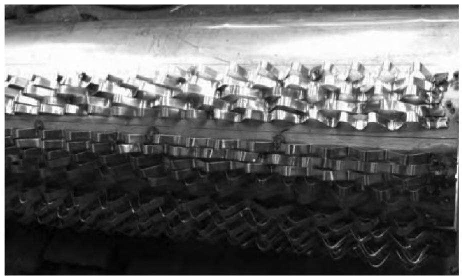

图 3　制造中的波形板扰流件

Fig. 3 The corrugated plate disturbed flow component during manufacturing

2　实验结果与讨论

2.1　对流传热的试验关联式

图 4 为管内装有波形板扰流件后的努赛尔数 Nu - 雷诺数 Re 数据汇总。经线性回归,其对流传热关联式为:

$$Nu = 0.0013Re^{1.25}Pr^{0.4} \tag{1}$$

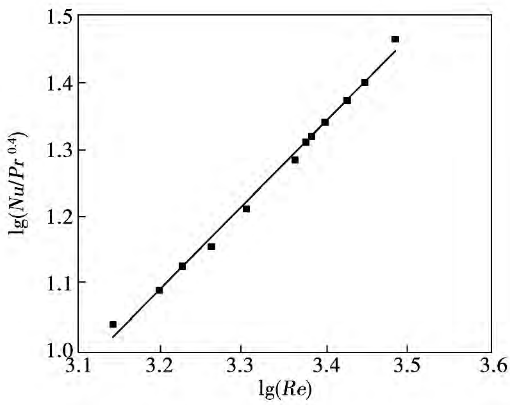

图 4　管内加装波形板扰流件后的气体努赛尔数 Nu - 雷诺数 Re 数数据汇总

Fig. 4 Nu-Re of gas heat transfer in tube with corrugated plate

式(1)中采用烟气的平均温度 t_f(即烟气进、出口温度的算术平均值)为定性温度，取烟气流通截面的当量直径 d 为特征尺寸。试验范围为 $1\,300 < Re < 3\,500$，烟气温度范围为 550－800 ℃。数据的相对偏差在 ±8.2% 内。其中，烟气的辐射换热是通过试验段管内无波形板扰流件情况下得出的，即分别由传热方程式算出烟气的总传热系数和 Dittus－Boelter 公式算出对流传热系数，两者之差即为烟气的辐射传热系数。当管内有波形板扰流件时，其它试验条件与无波形板扰流件时相同，得出的总传热系数减去已求出的辐射传热系数，即求得有波形板条件下烟气的对流传热系数；烟气近似为常物性，故规定普朗特数 Pr 的指数为 0.4，由此引起普朗特数 Pr 的最大误差为 5.33%。

2.2 波形板扰流件的强化对流传热分析

图 5 为管内有、无波形板扰流件时的对流传热性能比较。

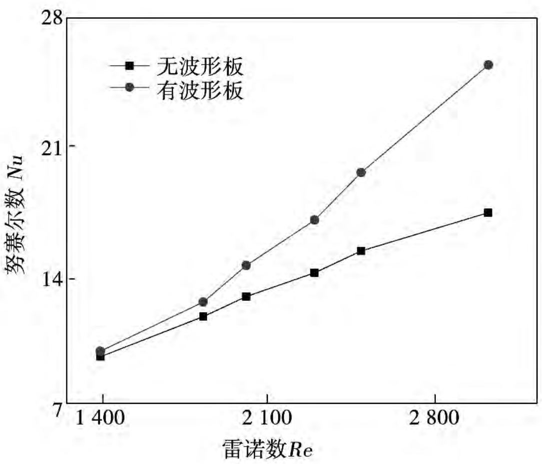

图 5 管内有、无波形板扰流件时的气体对流传热性能比较

Fig. 5 Comparsion of convection heat transfer performance in tube with and without corrugated plate

由图 5 看出，两种情况下，管内高温烟气对流传热的努赛尔数 Nu 均随雷诺数 Re 的增大而增大，所不同的是装有波形板扰流件后努赛尔数 Nu 随雷诺数 Re 的增长速率明显变大。这可能是因为，波形板扰流件使管内烟气流动的紊乱度明显提高，烟气的流动产生径向分速度，机械位移增强，使得对流传热性能得到提高，这也符合强化对流传热的场协同理论[16]，即波形板扰流件提高了速度场与热流场的协同程度。

文献[17]规定，对流传热强化率 E 是指强化前后传热系数与传热面积乘积之比，以表示扰流件强化对流传热的程度，强化率 E 表达式为:

$$E = (hA)_c / (hA)_p \tag{2}$$

波形板的对流传热强化率 E 随雷诺数 Re 的变化如图 6 所示，强化率 E 随着雷诺数 Re 的增加而增加，波形板扰流件的对流传热强化率为 1.6－3.5。

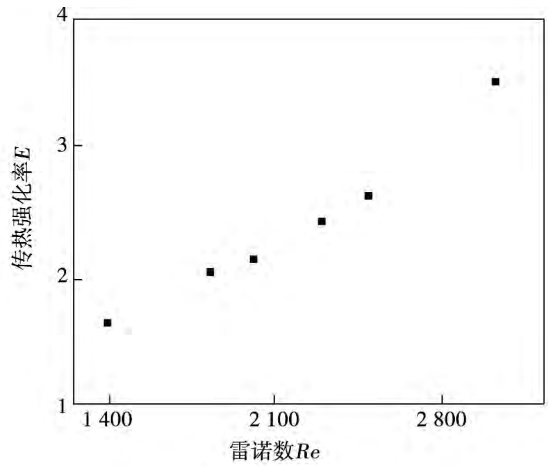

图 6 传热强化率 E 与雷诺数 Re 的变化关系

Fig. 6 Variation of the enhancement ratio with Reynolds number

图 7 为本研究与文献[14]加装波形板扰流件的管内气体对流传热性能比较。其中，文献[14]试验研究的波形板几何尺寸为 $S/d = 2.98$，$U/d = 0.25$，而本研究波形板几何尺寸为 $S/d = 0.5$，$U/d = 0.25$。从图 7 看出，本研究的波形板对流传热努赛尔数 Nu 均高于文献[14]的结果，而本研究的波形板 S/d 小于文献[14]，这说明波形板 S/d 越小，对强化传热越有效。事实上，当 S/d 减少时，意味着相同距离内波形板的波数变大，流体的扰动频率增加，紊流度增强，垂直于波形板的分速度也会增加，因而增强了对流传热。

2.3 管内波形板扰流件的阻力特性分析

图 8 为管内有、无波形板扰流件时的阻力降 $\triangle P$ 随雷诺数 Re 的变化关系。由图 8 看出，两种情况下，管内高温烟气的阻力降 $\triangle P$ 均随着雷诺数 Re 的增大而增大，装有波形板扰流件后的阻力降明显高于无波形板扰流件时的情况，这说明对流传热的

增强以阻力增加为代价。

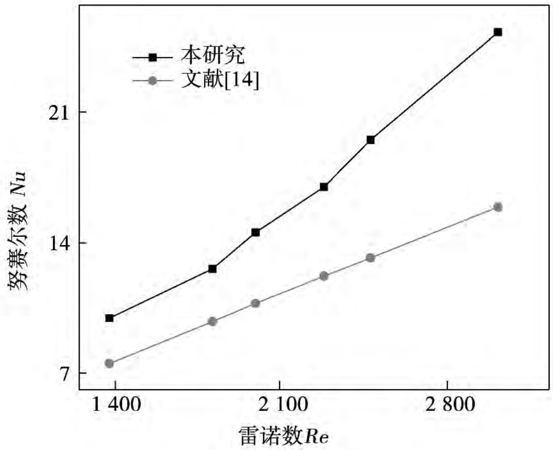

图 7　加装波形板扰流件后的管内气体传热性能比较

Fig. 7 Comparsion of gas heat transfer performance in tube with corrugated plate

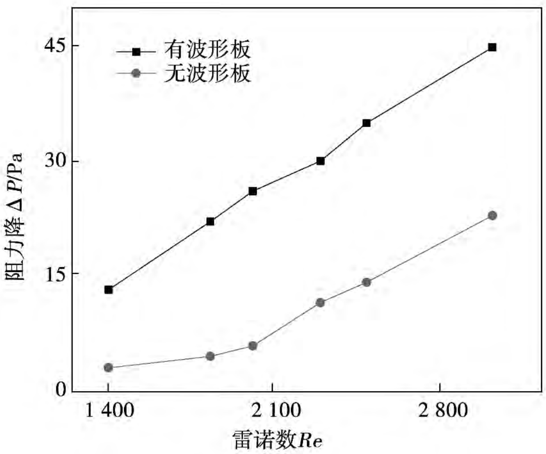

图 8　管内有、无波形板扰流件时的阻力降△P 和雷诺数 Re 的变化关系

Fig. 8 Variation of resistance drop △P and Reynolds number in tube with and without corrugated plate

图 9 为管内有、无波形板扰流件时的阻力系数 ζ 随雷诺数 Re 的变化关系。阻力降△P 计算式为:

$$\Delta P = \zeta \frac{l}{d} \frac{\rho v^2}{2} \tag{3}$$

由图 9 看出,随着烟气雷诺数 Re 的增加,管内有波形板扰流件的阻力系数 ζ 比无波形板扰流件的大,两者间的差距随雷诺数 Re 的增大而缩小。这可能是因为随着雷诺数 Re 的增加,流体本身的紊流度增强,波形板扰流件对烟气的扰动作用相对减弱。

在试验范围($1\ 300 < Re < 3\ 500$) 内,对管内装有波形板扰流件的阻力系数 ζ 随雷诺数 Re 变化进行回归分析,关联式为:

$$\zeta = 3\ 560 Re^{-1.323} \tag{4}$$

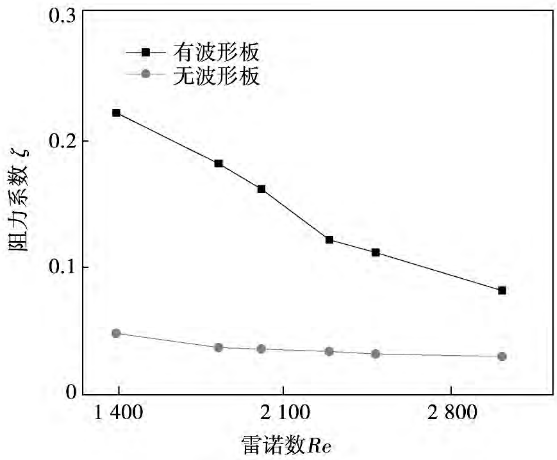

图 9　管内有、无波形板扰流件时的阻力系数 ζ 和雷诺数 Re 的变化关系

Fig. 9 Variation of drag coefficient ζ with Reynolds number in tube with and without corrugated plate

2.4　传热强化性能评价指标

传热强化性能评价指标是指在规定输送泵功和传热面积的条件下,以传递热量的大小作为强化传热的评价准则。准则数越大,强化传热综合性能越好[18]。图 10 为管内有波形板扰流件时的传热强化性能指标 η 随雷诺数 Re 的变化。

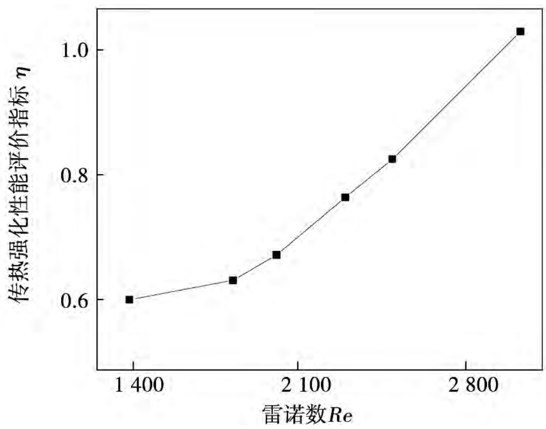

图 10　管内加装波形板扰流件时的传热强化性能评价指标 η 和雷诺数 Re 的变化关系

Fig. 10 Variation of heat transfer enhancement performance evaluation indicator with Reynolds number in tube with corrugated plate

$$\eta = \left(\frac{Nu}{Nu_0}\right) / \left(\frac{\zeta}{\zeta_0}\right)^{1/3} \quad (5)$$

由图 10 看出,传热强化性能评价指标 η 随着 Re 数的增大而增大,当 $Re > 3\ 000$ 时,η 值大于 1,说明此时对流传热强化比阻力降增加快,说明波形板扰流件综合强化效果越好。

3 结 论

(1) 波形板扰流件能有效强化管内小雷诺数 Re 气流的对流传热,且随着雷诺数 Re 增大,传热强化效果越好。本研究中,波形板扰流件的对流传热强化率为 1.6 - 3.5。

(2) 在管内插入波形板扰流件后,随着雷诺数 Re 的增加,气流的流动阻力也增加,波形板扰流件综合强化传热效果越好。

(3) 给出了试验范围($1\ 300 < Re < 3\ 500$) 内的管内加装波形板扰流件后的对流传热关联式与无因次阻力系数关联式。

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(丛 敏 编辑)

水下航行器动力系统螺旋管式蒸发器建模及动态仿真 = Establishment of a Model for a Spirally-coiled Tube Type Evaporator in a Underwater Vehicle Power System and Its Dynamic Simulation [刊，汉] BAI Jie, DANG Jian-jun, LI Dai-jin (College of Marine Navigation, Northwest Polytechnical University, Xi'an, China, Post Code: 710072) //Journal of Engineering for Thermal Energy & Power. -2016, 31(1). -27-31

According to the idea given in the moving boundary method, established was an all-inclusive moving boundary method-based model and a quasi-steady-state model for spirally-coiled tube type evaporators and prepared was an off-design condition dynamic simulation and calculation program. With a stepped change in the water flow rate at the inlet of the evaporator serving as the input condition, a simulation calculation was performed and such dynamic characteristics of the evaporator as the pressure inside the evaporator, outlet temperature and lengths of various phase zones etc. were obtained. The calculation results verified that the calculation methods under discussion are feasible and stable. Among them, the quasi-steady-state method uses fewer variables, thus favorable to the design of controllers and quicker in numerical calculation. When three phase zones are present in the evaporator, to conduct a calculation by using the moving boundary method is more rational and accurate. **Key words:** spirally-coiled tube, evaporator, dynamic simulation

管内加装波形板扰流件强化对流传热的试验研究 = Experimental Study of the Intensified Convection Heat Transfer in a Tube Additionally Installed with Corrugated Plate Flow Disturbers Inside the Tube [刊，汉] DING Shao-wei, LI Ju-xiang, ZHANG Su-jun (College of Energy Sources, Nanjing Polytechnic University, Nanjing, China, Post Code: 211816) //Journal of Engineering for Thermal Energy & Power. -2016, 31(1). -32-36

By using various test methods, studied were the convective flow heat transfer and resistance characteristics of the flue gases at a high temperature in a tube additionally installed with corrugated plate flow disturbers inside the tube under the condition of the Reynolds number being small and compared were the test results with those obtained in absence of the corrugated plates and calculated by using the empirical formulae respectively. It has been found that after the corrugated plate flow disturbers have been installed inside the tube, the convective flow heat transfer performance of the flue gases at a high temperature can be notably enhanced and with an increase of the Reynolds number, the enhancement effectiveness will become better and better. The convective flow heat transfer enhancement rate of the corrugated plate flow disturbers ranges from 1.6 to 3.5. As per the test results, a correlation formula of the heat quantity transferred and resistance coefficient of the tube installed with corrugated plate flow disturbers inside

the tube within the test range ($1300 < Re < 3500$) was summarized. **Key words**: convective flow inside a tube, Reynolds number, corrugated plate flow disturber, enhanced heat transfer

前驱体液滴在射频感应等离子体中的蒸发和传热传质 = Evaporation, Heat and Mass Transfer of the Precursor Liquid Drops in the Radio Frequency-induced Plasma [刊,汉] SONG Zhuo-lin, SHAN Yan-guang, XU Lian-si (School of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093) //Journal of Engineering for Thermal Energy & Power. -2016, 31(1). -37-41

A movement and evaporation model for liquid drops in a radio frequency-induced plasma jet flow was established to simulate the evaporation, heat and mass transfer of the precursor liquid drops. According to the mass, momentum and energy conservation equations, a method for controlling time-changing systems was used to predict the movement and evaporation of the liquid drops inside the plasma induced and coupled by radio frequencies and obtain the changes in the radii of the liquid drops and temperature on the surface of liquid drops as well as temperature distribution inside the liquid drops. With an increase of the initial sizes of the liquid drops and their residence time duration in the low temperature zone of the hot plasma, the surface of the liquid drops will be slowly and uniformly heated, thus the time required by the surface solute concentration to reach its saturated concentration becomes longer and the changing rate of the radius smaller. With an increase of the initial speed of the liquid drops and the environmental temperature experienced by the liquid drops, the evaporation speed of the liquid drops on the surface becomes quicker, the change in the radius smaller and the time required by the solute to be crystallized and separated becomes shorter. **Key words**: radio frequency plasma, evaporation, heat and mass transfer

预热微通道内制冷剂对沸腾换热系数影响的实验研究 = Experimental Study of the Influence of the Refrigerant Preheated on the Boiling Heat Exchange Coefficient Inside a Micro Channel [刊,汉] GE Qi-lin, LIU Jian-hua, ZHANG Liang, LIU Qi (College of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093) //Journal of Engineering for Thermal Energy & Power. -2016, 31(1). -42-47

In a stainless steel-made micro channel having an inner diameter of 2 mm, an experimental study of the boiling heat exchange characteristics of the refrigerant R 290 was performed. The test conditions were given as follows: the mass flow rates of the refrigerant were 150 and 330 $kg/m^2.s$ respectively, the heat flux densities of the refrigerant in the