文章编号: 1001－2060(2002)01－0017－03

平板间充填颗粒和壁面开槽时的流动与传热强化特性的实验研究

张志军, 程惠尔, 汤宇浩
(上海交通大学 动力与能源工程学院, 上海　200030)

摘　要: 提出了在平行平板间填充颗粒的同时, 运用板面加开微型纵槽构成复合多孔介质, 以改善流体流动与传热综合性能的方案, 并报道了实验结果及其分析。研究的结果表明, 对于这种复合多孔结构, 在适宜的颗粒直径 d_p、槽宽 w、槽深 d 及板间距 δ 匹配下, 传热比未开槽时有明显提高, 而流动阻力却有所下降, 因而证明是综合提高多孔介质强化传热技术经济性的有效措施。

关　键　词: 复合多孔结构; 强化传热; 板面开槽
中图分类号: TK124　　文献标识码: A

符号说明

d—微槽的深度, mm
d_p—板间填充的玻璃珠颗粒的平均直径, mm
f—流动的阻力摩擦系数
N—板面上加开微槽数目
Δp—流体流过实验件的压降, Pa
u_c—微槽内流体流速, $m \cdot s^{-1}$
u_m—板间填充颗粒时的表观平均流体流速, $m \cdot s^{-1}$
δ—平行平板间的距离, mm
ρ—流体(水)的密度, $kg \cdot m^{-3}$
d_e—微槽截面的水力当量直径, mm
E—板面加开微槽带来的传热面积比, 见式(1)
L—换热板上有效传热区域的长度, mm
Re_c—以微槽截面当量直径定义的微槽内流动 Reynolds 数
u^*—式(5)定义的无量纲流速
w—微槽宽度, mm
μ—流体(水)的动力粘度, $kg \cdot m^{-1} \cdot s^{-1}$

1　引言

理论分析和实验结果都表明[1~2], 单相流体通道内填充圆形颗粒后, 能够显著增强流体和壁面的换热, 但流动阻力甚至增加得更多, 从而限制了这种强化传热方式的应用领域。作者进行了平行平板间填充小颗粒玻璃珠以强化单相流体受迫对流传热的实验研究[3~5], 表明小颗粒填充比细微颗粒填充时强化换热具有更好的技术经济性, 在化工、食品工业、节能等领域有着潜在的应用前景。

在靠近壁面的区域内, 多孔介质孔隙率将明显大于中心主流区, 温度梯度和流速梯度都主要集中在近壁区, 该区域是进一步改善填充多孔介质传热效果的主要环节。为此, 本文对在板间填充颗粒的同时在板面加开纵向微槽构成的复合多孔结构进行实验测试的研究。

2　实验系统

实验系统见图 1, 主要由热源箱、热水循环泵、实验件、冷热流体管道和测量系统组成, 所用冷、热介质均为水。换热板的有效换热区宽度为 90.0 mm, 颗粒填充长度为 180.0 mm。

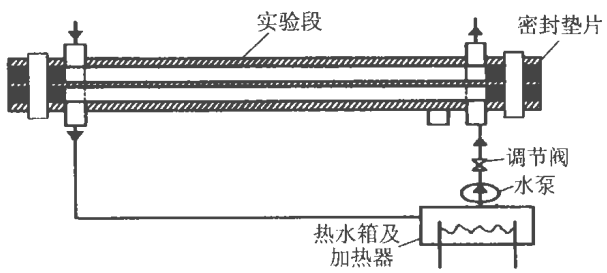


图 1　实验系统简图

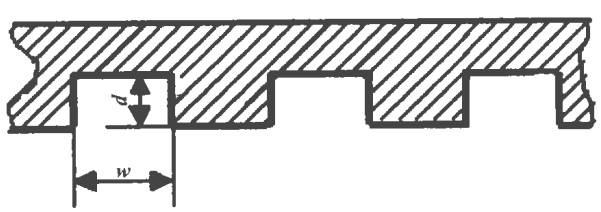


图 2　开槽板结构示意图

采用加开不同尺寸纵向微槽的换热片(见图 2), 分别进行了不填充和填充玻璃珠颗粒时的试验, 以确定板面加开纵向微槽对流动与传热带来的影响。开槽参数如表 1 所列。

收稿日期: 2000－11－09; 修订日期: 2000－12－18
基金项目: 国家重点基础研究发展规划基金资助项目(G19999022303)
作者简介: 张志军(1968－), 男, 山东泰安人, 上海交通大学博士后。

表 1 传热板片表面的微槽几何尺寸

	板 A	板 B	板 C
w/ mm	0.5	0.5	1.0
d/mm	0.5	1.0	1.0
d_e/mm	0.5	0.667	1.0
n	16	16	16
E	1.178	1.356	1.356

表 1 中的传热面积比 E 为开槽后板的表面积/开槽前板的表面积, 即

$$E = \frac{L\times(90+2nd)}{L\times 90} \qquad (1)$$

3 实验结果及分析

在处理实验数据时, 传热面积按未开槽时的平板面积计算, 定性尺寸为未开槽时的板间截面当量直径, 以与壁面未开槽时的实验结果进行对比。Reynolds 数 Re 统一按板间平均 Darcy 流速计算。实验结果如图 3 ~ 图 6 所示。

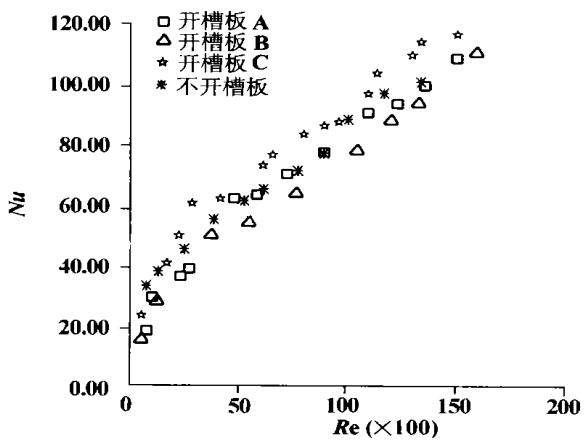
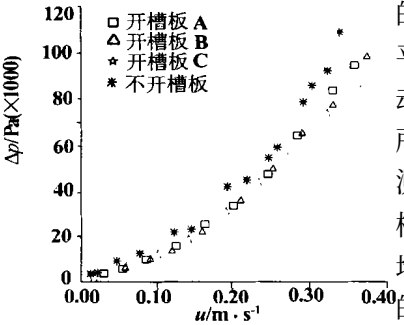


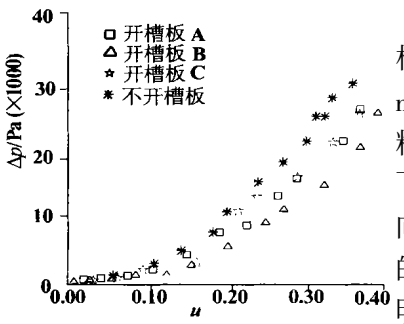
图 3 板间不填充颗粒时板面开槽对换热的影响 (δ= 10.5 mm)

图 3 给出板间距 δ= 10.5 mm 时表面未开槽平板和 3 块表面开槽平板在不填充颗粒时的换热结果。与未开槽平板相比, 开槽尺寸为 1.0 mm × 1.0 mm 的 C 板 Nu 数略有增加, 开槽尺寸为 0.5 mm × 1.0 mm 的 A 板 Nu 数基本不变, 而开槽尺寸为 0.5 mm × 0.5 mm 的 B 板 Nu 数似略有下降。总的说来, 考虑到 Nu 的实测不确定度, 板面开槽对于未填充颗粒时的传热并无明显影响。

图 4 给出了板间距 δ= 10.5 mm 时在填充不同粒径颗粒情况下换热壁面开纵向微槽对于流动的影响。图中表明, 板面开纵向微槽后, 由于截面流通面积有所增加, 更由于微槽内的流动阻力减小, 微槽内的流速大于截面平均流速, 因此流动阻力系数 f 有所下降。可以推测, 当板面上开微槽的密度进一步增加时, 流动阻力的下降会更显著, 表明这是减小流阻的有效方式。



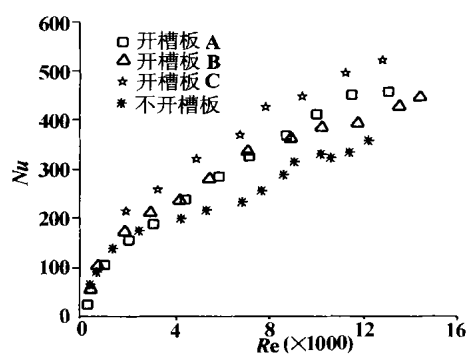
(a) d_p = 2.0 mm



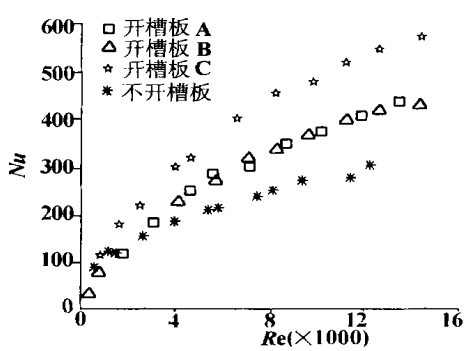
(b) d_p = 5.5 mm

图 4 δ= 10.5 mm, 填充颗粒时开槽对流动的影响

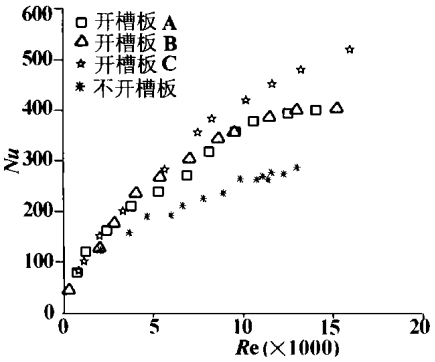
图 5 给出了板间距 δ= 10.5 mm 时在填充不同粒径的颗粒情况下换热壁面开纵向微槽对于传热的影响。图中表明, 板面开纵向微槽后, A、B、C 三种板, 填充不同粒径颗粒时 Nu 均有明显增加。C 板的传热效果好于另外两种板, Nu 约增加 40% 左右。图 5 还表明, 板面开槽对传热的强化, 随着流速的增大效果越明显。这是因为微槽内流动阻力系数小, 使槽内流速的增加大于板间平均流速的增加, 具有较强向板面传热的能力。实验结果表明微槽的尺



(a) d_p = 2.0 mm



(b) d_p = 3.5 mm



(c) d_p = 5.5 mm

图 5　δ= 10.5 mm 时壁面开槽对换热的影响

寸和颗粒直径及板间距等因素之间存在着一定的优化匹配关系。

4　板面开槽流动状况的简化模型分析

结合上述实验结果, 尝试应用简化的近似模型进行分析。

假设微槽宽度 w 小于颗粒粒径 d_p, 纵向微槽内和微槽开口处与板间多孔介质填充区在流动方向即 x 方向的沿程压力梯度相等, 即

$$p_p(x) = p_c(x) \tag{2}$$

考虑槽道开口的影响, 微槽内流动的摩擦阻力系数按下式计算[6]:

$$f = \frac{d_e}{L} \times \frac{\Delta p}{2\rho u_c^2} = \frac{79}{Re_c} \tag{3}$$

其中 $Re_c = \dfrac{\rho u_c d_e}{\mu}$, 整理后得到

$$u_c = \frac{d_e^2}{L} \times \frac{\Delta p}{158\mu} \tag{4}$$

由式(4)求得板间距 δ= 10.5 mm 时3种开槽板分别填充 d_p = 5.5 mm 的颗粒下微槽内的流速 u_c, 如图6所示。图中纵坐标为由式(5)定义的以 u_m 为基准度量的微槽内的无量纲流速 u^*。

$$u^* = u_c / u_m \tag{5}$$

从图 6 可见: 在同样的压降下, C 板微槽内的流速远大于板间平均流速, B 板在压降超过一定值, 或者说板间平均流速超过一定值后, 微槽内流速才明显大于板间平均流速, 而在本实验压降范围内, A 板微槽内的流速基本与板间平均流速相当, 在较小压降下甚至低于板间平均流速。因此, C 板微槽内的流动状态易于在较小的板间平均流速时就达到紊流, 有明显较强的换热强度; 而 A 板和 B 板的微槽内流动阻力系数较大, 当所填充的颗粒直径较大时, 多孔介质本身的流动阻力较小, 微槽内处于层流状态, 微槽壁面的传热强度较弱, 传热增强的效果就不如 C 板。这表明, 为了利用壁面开纵槽在板间填充颗粒的同时取得较好的效果, 需要开槽尺寸和颗粒粒径之间保持适当的匹配关系。这种优化匹配, 值得继续深化研究。

5　结束语

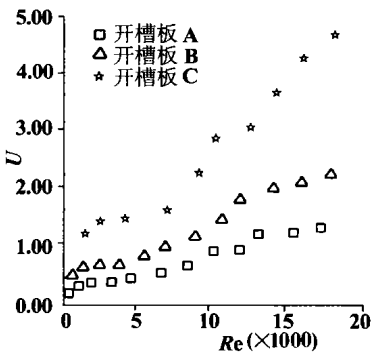


图 6　微槽内流速与板间平均流速的比较

(δ= 10.5 mm, d_p = 5.5 mm)

综上所述, 本文提出的特定的复合多孔结构, 可在一定条件下显著增强板间流体与板面的换热强度, 同时流动阻力却有所下降, 从而取得更好的流动与传热的综合经济效益。在板面上加开纵向矩形微槽, 具有易于加工、容易实现的优点, 同时板间填充颗粒, 起到强化传热、支撑的作用, 能够简化目前复杂板型的板式换热器的结构及其制造。本文的实验结果表明, 应进行更大范围板间距、微槽尺寸、颗粒直径的实验, 以取得更充分的实验依据, 探索有关板间距、填充颗粒粒径、微槽尺寸和分布的最优化匹配。

参考文献:

[1] FU W S, HUANG H C, LIOU W Y. Thermal enhancement in laminar channel flow with a porous block[J]. **Int J Heat Mass Transfer**, 1996, **39**(10): 2165－2175.

[2] VARAHASAMY M, FAND R M. Heat transfer by forced convection in pipes packed with porous media whose matrices are composed of spheres[J]. **Int J Heat Mass Transfer**, 1996, **39**(18): 3931－3947.

[3] FAND R M, VARAHASAMY M, GREER L S. Empirical correlation equations for heat transfer by forced convection from cylinders embedded in porous media that account for the wall effect and dispersion[J]. **Int J Heat Mass Transfer**, 1993, **36**(18): 4407－4418.

[4] 王补宣, 张志军, 杜建华. 平行平板间填充球粒填料的传热特性试验研究[J]. 工程热物理学报, 1999(2): 220－223.

[5] 王补宣, 张志军, 杜建华. 小尺度多孔介质板式换热器的可行性实验研究[J]. 清华大学学报, 1999(10): 39－41.

[6] 张志军. 多孔介质强化板式换热器性能的基础研究[D]. 北京: 清华大学, 1999.

(何静芳　编辑)

fer, temperature fluctuation

平板间充填颗粒和壁面开槽时的流动与传热强化特性的实验研究= **Experimental Investigation of the Flow and Heat Transfer Intensification Characteristics for Parallel Plates with Beads Packed Between Them and Slotted Plate Wall Surface** [刊, 汉] / ZHANG Zhi-jun, CHENG Hui-er, TANG Yu-hao (Power and Energy Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —17 ~ 19

With beads packed between parallel flat plates and mini-longitudinal slots opened on plate surface, composite porous media were formed to improve fluid flow and heat transfer comprehensive performance. The results of the investigation were reported and analyzed. They indicate that under this kind of composite porous construction the proper matching of bead particle diameter, slot width, slot depth and clearance between plates can lead to a significant enhancement of heat transfer performance as compared with the case of flat plates with no slots provided. Meanwhile, flow resistance has been somehow lowered. The positive results thus obtained prove that the proposed measures are highly cost-effective in achieving an intensified heat transfer in porous media. **Key words**: composite porous media, intensified heat transfer, slotted plate surface

循环流化床锅炉燃烧室边界层的实验研究= **Experimental Study of a Boundary Layer in the Furnace of a Circulating Fluidized Bed Boiler** [刊, 汉] / LU Jun-fu, LIU Qing, ZHANG Jian-sheng, et al (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering For Thermal Energy & Power. —2002, 17(1). —20 ~ 22

The raw material concentration in the furnace of a circulating fluidized bed boiler may affect heat transfer and fuel combustion. By measuring the raw material concentration distribution in the furnace of a 75 t/h circulating fluidized boiler it was discovered that there exists near a wall surface a gas boundary layer in the down flow boundary layer of the above-cited furnace. The thickness of the gas boundary layer varies with its distance from the air distribution plate height. On this basis a formula was given for calculating the thickness of the down flow boundary layer and the gas boundary layer. In addition, a double annulus model of the circulating fluidized bed boiler furnace is also proposed. **Key words**: circulating fluidized bed boiler, combustion furnace, boundary layer, double-annulus model

增压条件下石灰石固硫机理实验研究= **Experimental Study of Limestone-based Desulfurization Mechanism under a Supercharged Pressure** [刊, 汉] / YU Ming-zhi (Department of Air Conditioning Engineering, Shandong Architectural Engineering Institute, Jinan, Shandong Province, China, Post Code: 250014) // Journal of Engineering for Thermal Energy & Power. —2002, 17(1). —23 ~ 26

The use of a pressurized fluidized bed combined cycle (PFBC-CC) plant for power generation can be conducive to enhancing power generation efficiency and solving issues of environmental pollution. This technology has currently reached the stage of industrial pilot test and specific applications. The research of limestone-based desulfurization characteristics at supercharge-pressure combustion conditions has been listed as one of the key research themes of PFBC clean combustion. Under a relatively high CO_2 partial pressure the limestone is not liable to calcination decomposition, thus making the mechanism of limestone-based desulfurization at a supercharged pressure different from that at a normal pressure combustion condition. With the help of a pressurized test rig the author has conducted an experimental study of the limestone-based desulfurization characteristics. Furthermore, a JXA-80 electronic scanning microscope was employed to conduct a microscopic detection analysis along with the determination of desulfurization media. **Key words**: limestone, super-