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纳米流体在泡沫金属管内强化换热的数值模拟

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摘 要: 本研究通过在流体流过的管内核心区插入不同半径的泡沫金属、在基液中添加纳米粒子的方法达到强化换热的目的。通过泡沫金属管与光管内温度场及速度场的比较来分析泡沫金属对强化换热的作用,研究了泡沫金属填充比和纳米流体对流动及换热性能的影响。研究表明: 模拟结果与文献实验结果吻合良好,将泡沫金属填充在管内核心区可以提升换热特性,而纳米流体的加入可以使换热效果增强。在低流速的条件下,换热效果随填充比和纳米流体浓度增大而增强,但泡沫金属填充比和纳米流体体积分数之间存在最佳搭配。研究可知,在填充厚度为6 mm、纳米流体体积分数为0.3%时综合换热性能最佳; 流速和填充比的增大有利于强化换热,但压降也随之增大。

关 键 词: 泡沫金属; 纳米流体; 强化换热; 数值模拟

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引 言

开孔泡沫金属作为新兴的多孔介质,具有比表面积大、导热系数高、流体混合能力强等诸多优良的热物理性。填充泡沫金属通道的换热能力最高可为同等尺寸光管通道的50~1 000倍。近些年,泡沫金属在紧凑式换热器、航天航空、军事领域有着非常大的应用前景[1]。而新型换热介质—纳米流体同样具有稳定、高导热的性能[2],成为传热学领域的研究热点。

Mohamed对部分填充及全部填充多孔介质的圆管内流体的换热性能进行了比较[3],发现部分填充多孔介质圆管的换热性能比全部填充好,流动阻力更小; 在文献[4]中把边界层以外的区域称为核心流区。传统管内强化换热技术都把重点放在热边界层内,而如今的研究也表明在核心区的温度也存在一定梯度。Liu和杨雯瑾对通道内填充多孔介质对流换热进行研究[5~6],结果表明在流体的核心区填充多孔介质可使该区域温度极大的均匀化。在填充泡沫金属通道中加入纳米流体可提高导热能力,这是纳米技术应用于热能工程这一传统领域的创新性的研究。首先,纳米流体在泡沫金属管中物性稳定,其良好的导热性能和微粒子的布朗运动可显著增强换热[7],钟勋等对纳米流体在发动机油冷器中强化传热进行研究[8],结果表明纳米流体的流动和传热性能均具有温度增益特性; 其次,低浓度的纳米流体可以改善泡沫金属管压降大的弊端。Raed等研究发现[9],将纳米流体与多孔介质结合可以达到双重强化换热的效果。因此纳米流体在泡沫金属管内的双重强化换热研究可以对换热要求极高的散热器等设计提供指导[10~11]。

关于泡沫金属和纳米流体单独作用的研究已有大量文献,但是多数研究的是纳米流体或泡沫金属自身材料功能及换热特性,在泡沫金属填充手段上也大多采用的是环状填充或全填充的方式,鲜有将核心区填充泡沫金属和纳米流体结合进行研究及应用的讨论。因此本文对核心区填充泡沫金属管内纳米流体流动和传热进行研究,运用Fluent 14.0软件进行计算,得到管内温度场速度场及换热系数,分析泡沫金属填充厚度、纳米流体浓度及雷诺数对泡沫金属管换热及阻力系数的影响,为多孔介质及纳米流体双重强化换热技术应用到多孔介质换热器或太阳能集热器等设备中提供设计参考。

1 数值模拟

1.1 物理模型

本文对在管内流动核心区填充铜泡沫金属的圆

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管进行建模如图 1 所示。管内径为 8 mm，壁厚 1 mm，热流密度 q，所填充的铜泡沫金属内径为 r，含 Al_2O_3 纳米颗粒的流体在管道内流动。边界条件为速度入口压力出口，流体入口温度恒定为 300 K，入口速度由雷诺数 Re 决定（$40 < Re < 2\ 000$），选择层流模型、多孔介质模型并开启能量方程，设置参数由公式（3 ~6）确定。设置泡沫金属填充比为 $r_i = r/R$，r_i 的研究范围为 0.556 ~0.889。

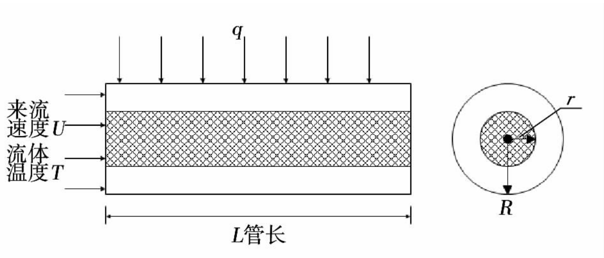

图 1　泡沫金属管物理模型

Fig. 1 Physical model for foam metal tubes

1.2　数学模型及相关假设

为计算方便，对数学模型作如下简化：假定泡沫金属均匀且各向同性；泡沫金属内部固体骨架与流体之间满足局部热平衡；忽略流动的粘性热效应；忽略管壁的导热；流体和固体的物性参数为常数；忽略自然对流和辐射换热；流体不发生相变，纳米流体为两相流。

结合以上假设，所述问题的控制方程如下：

质量方程：

$$\nabla \cdot [V] = 0 \tag{1}$$

动量方程：

$$\frac{\rho_f}{\varepsilon}[(V\cdot\nabla)V] = -\frac{1}{\varepsilon}\nabla[p]_f + \mu_{eff}\nabla^2[V] - \left[\frac{\mu_f}{K} - \frac{\varepsilon\rho_f C_i}{\sqrt{K}}\right][V] \tag{2}$$

式中：V—流体速度，m/s；ε—泡沫金属孔隙率；ρ_f—流体密度，kg/m^3；μ_{eff}—有效粘性系数，kg/(m·s)；μ_f—流体动力粘度，kg/(m·s)；K—泡沫金属渗透率，m^2；C_i—惯性系数，kg/(m·s)。

根据 Bhattacharya 等的研究[12]，泡沫金属渗透率 K 及惯性系数 C_i 可由以下公式计算：

$$K = \frac{\varepsilon d_p^2}{108(b-1)} \tag{3}$$

$$b = \frac{4\varepsilon}{\pi(1-a^2)} \tag{4}$$

$$a = 1.18\sqrt{\frac{1-\varepsilon}{3\pi}}\cdot\frac{1}{1-e^{-(1-\varepsilon)/0.04}} \tag{5}$$

$$C_i = 0.009\ 5\,[1-e^{-(1-\varepsilon)/0.04}]^{-0.8}\cdot\frac{1}{a}\sqrt{\frac{\varepsilon}{3(b-1)}} \tag{6}$$

式中：a—泡沫金属纤维直径与孔径之比。

能量方程：

$$\rho c[V]\cdot\nabla[T] = \nabla(k_{eff}\cdot\nabla^2[T]) \tag{7}$$

式中：k_{eff}—有效导热系数，W/(m·K)；b—迂曲度；e—自然常数。

计算式如下：

$$k_{eff} = \varepsilon k_f + (1-\varepsilon)k_s \tag{8}$$

应用 Fluent 14.0 软件进行数值模拟，在网格划分时在近壁处及泡沫金属区域与主流区交界处进行网格加密处理。首先选取网格数量由 58 800 到 671 580的 6 套网格系统进行网格独立性考核，取管壁平均温度和流体流过整段圆管的压降作为检验网格无关性的两个参数，当网格数达到 143 100 时，壁面平均温度和压降的差别小于 0.1%，为节省计算资源，研究区域的网格数量取 16 万左右网格，此时数值解可视为网格独立解。整个求解过程在三维条件下进行采用 SIMPLE 算法，对压力和速度耦合方程进行求解，离散方程采用有限体积法和二阶差分格式，各计算量相对误差控制在 10^{-5} 以内，纳米流体采用离散相模型。

2　模拟结果与分析

2.1　模型验证

首先对充分发展状态下水和 Al_2O_3—H_2O 纳米流体在泡沫金属管内的流动换热进行数值模拟，在定温条件下将模拟所得局部努塞尔数 Nu 数和压降 $\triangle p$ 与文献[13]所得实验结果对比如图 2、图 3 所示。模拟所得 Nu 值、压降 $\triangle p$ 与实验值最大偏差分别为 4.8% 和 3.3%，认为模拟结果与实验结果相吻合，所使用的数值模型精度较高，对管内核心区填充泡沫金属并采用此模型求解时，在保持单元格大小不变的情况下对数值模型精度影响很小，所得模型是正确的。

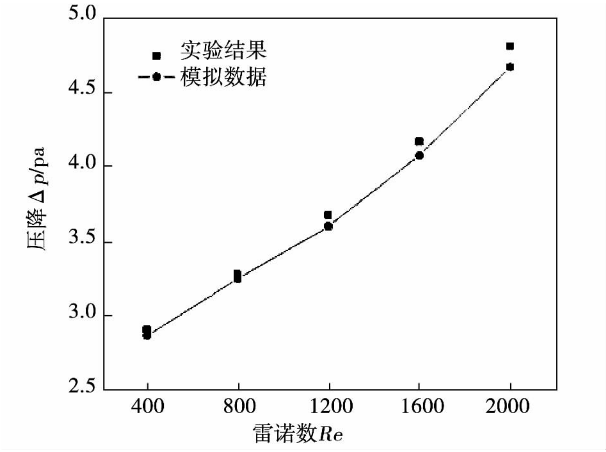

图 2　模拟所得压降 △p 数据与实验结果对比

Fig. 2 Contrast of the simulation result of the pressure drop △p with the test one

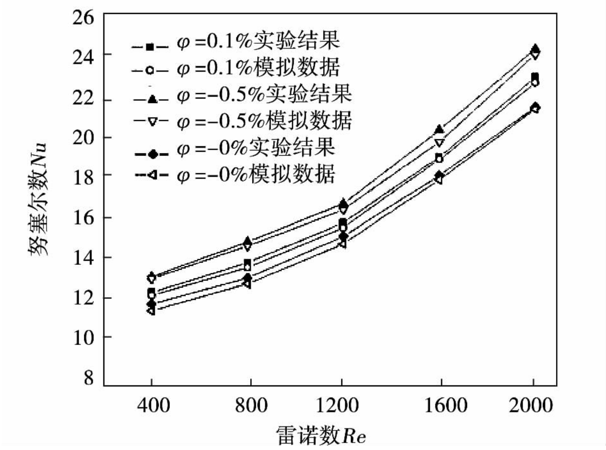

图 3　模拟所得努塞尔数 Nu 数据与实验结果对比

Fig. 3 Contrast of the simulation results of the Nusselt number with the test ones

2.2　速度场分布

图 4 给出了水在泡沫金属管内流动时的速度分布，与文献 [4] 所获得规律吻合良好。

在光管充分发展段，流速沿半径方向呈线性分布，且速度梯度较大；而在泡沫金属填充管内，即便泡沫金属渗透率很高但是其复杂的三维结构导致流体在核心区的流速很低，所以大多流体由未填充管处流出使得边界区流速增大。随着填充比的增大，高填充比的速度峰值明显高于低填充比的速度峰值，这是由于流体从多孔区域向非多孔区域流动时渗透率突增，导致流体流速迅速增加而在未填充泡沫金属的近壁处形成速度峰值，而高填充比的泡沫金属管由于非多孔区域更狭窄导致流速峰值更高。由此形成了流体在核心区速度分布均匀，只在非多孔区域出现较大速度梯度的现象。

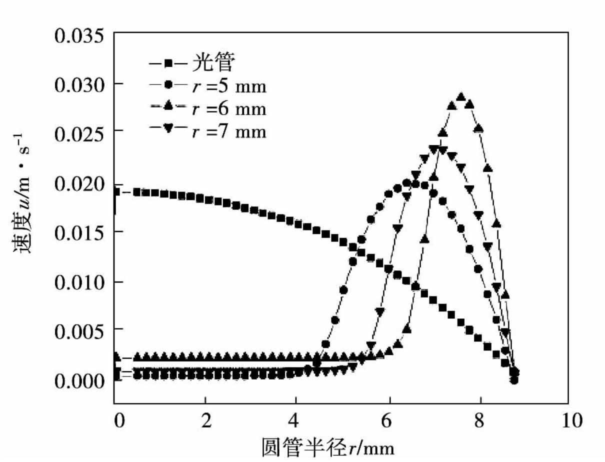

图 4　圆管内速度分布

Fig. 4 Distribution of the velocity inside a circular tube

2.3　温度场分布

图 5、图 6 分别给出水在泡沫金属管及光管同一径向截面的温度分布。

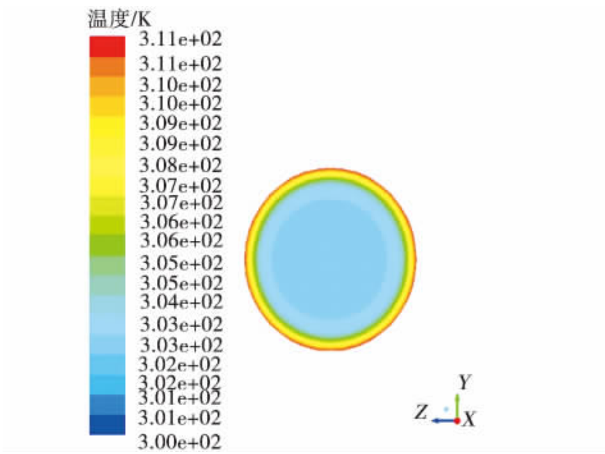

图 5　泡沫金属管内温度分布

Fig. 5 Distribution of the temperature inside a foam metal tube

泡沫金属的填充使温度在核心区分布均匀，泡沫金属区域内流体逃逸到主流区，使边界层厚度减小，泡沫金属区域有效导热面积随填充半径增加而增大，因此温度分布就越均匀，在近壁处的温度梯度就越大，由于速度剖面与温度剖面很大程度上均匀化具有很好的协同作用 [5]，并且根据牛顿冷却定律可知，对流换热系数随壁面与核心流温差的减小而增大，因此核心区域温度分布越均匀，换热得到强化的幅度越大。

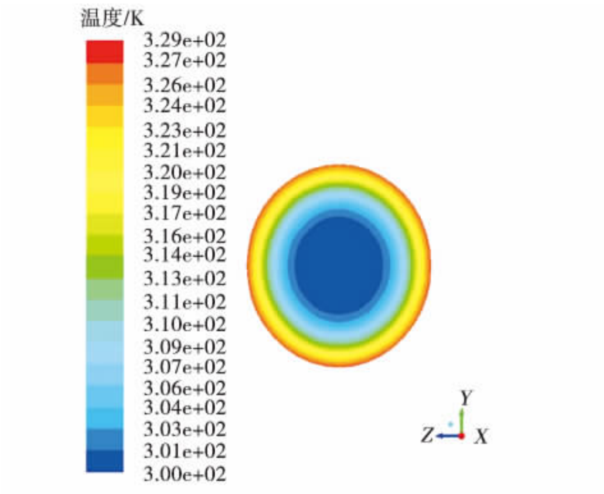

图 6 光管内温度分布

Fig. 6 Distribution of the temperature inside a bare tube

2.4 泡沫金属管与光管换热性能比较

图 7 给出了水在不同填充半径厚度的泡沫金属管与光管中换热性能比较。

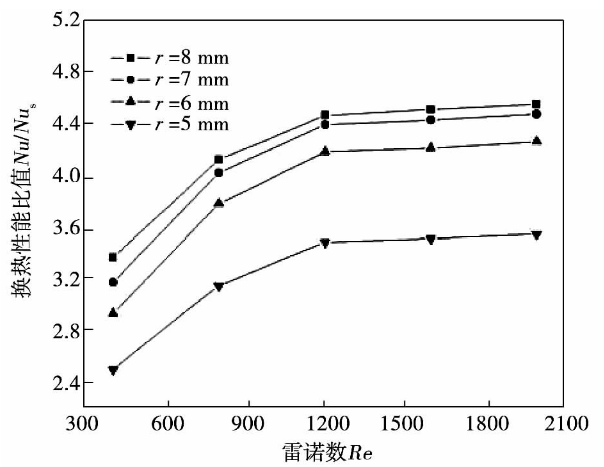

图 7 泡沫金属管与光管换热效果比较

Fig. 7 Comparison of the heat exchange effectiveness of a foam metal tube with that of a bare tube

整体上，泡沫金属填充比越高，换热效果越好，随着 Re 增大，换热效果呈上升的趋势，并且换热效果随 Re 增大而逐渐减弱。在低填充比的条件下，流体流动阻力小但泡沫金属的导热性能被削弱，流体与固体之间的比表面积减小，在光管区域的流动阻力与在泡沫金属区域的流动阻力接近，换热能力减弱；而在高填充比条件下，通流面积增大，流体会更加均匀的分布在径向截面中，管内流体的有效

导热系数对换热的效果影响明显。

2.5 泡沫金属管与光管阻力系数比较

图 8 表示水在不同半径厚度泡沫金属管与光管阻力系数比值随 Re 的变化。

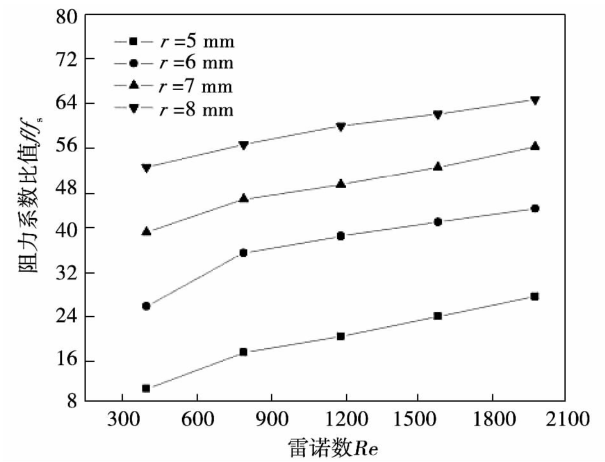

图 8 泡沫金属管与光管阻力系数比较

Fig. 8 Comparison of the resistance coefficient of a foam metal tube with that of a bare tube

泡沫金属孔隙率一定的条件下，随 Re 增大，泡沫金属管与光管阻力系数比值呈线性增大的趋势，这是由于管内核心区填充泡沫金属使得贴近管壁的边界形成较大的速度梯度，而泡沫金属内部错综复杂的固体结构和高比表面积是造成阻力系数增大的主要影响因素，因此随 Re 和填充厚度增加，能量耗散和流动阻力也随之增大。

2.6 填充厚度对综合换热性能的影响

采用下式作为强化换热方式的综合性能评价准则式[16]：

$$P_{EC} = \frac{Nu/Nu_s}{(f/f_s)^{1/3}} \tag{9}$$

式中：Nu—泡沫金属管的努塞尔数；Nu_s—光管的努塞尔数；f—泡沫金属管的阻力系数；f_s—光管的阻力系数。

该值表现了在等泵功情况下，泡沫金属管的换热性能。图 9 表示泡沫金属填充厚度对综合性能 P_{EC} 值的影响。P_{EC} 值随雷诺数增大呈先增大后减小的趋势，当 $400 < Re < 1\ 200$ 范围内，P_{EC} 逐渐增大，此时泡沫金属管换热能力增大速率大于阻力系数增大速率；当 $1\ 200 < Re < 2\ 000$ 范围内时，压降随雷诺数增大递增，努塞尔数 Nu 增大速率逐渐小于阻力系数 f 增大值，导致 P_{EC} 值下降。在所研究范围内，填充 6 mm 半径厚度泡沫金属的填充管 P_{EC} 值整体最高达到 1.27 左右，综合换热性能最佳。

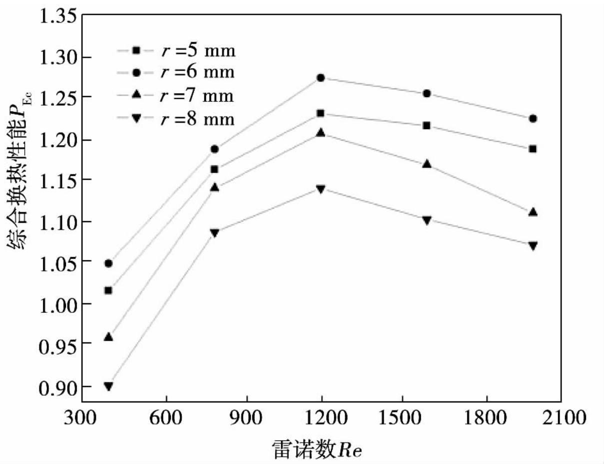

图9　填充厚度与综合换热性能的关系

Fig. 9 Relationship between the filling thickness and the comprehensive heat exchange performance

2.7　纳米流体浓度与换热性能的关系

图10表示纳米流体浓度与换热性能的关系。当Al_2O_3—H_2O纳米流体体积分数由0.1%增加到1%时，与普通基液的换热性能相比平均增加幅度为18.85%、24.43%和28.32%。这是由于随填充比增加，纳米流体与泡沫金属区域的比表面积增加，在孔隙率一定的条件下，泡沫金属填充比的增大使得流固之间的换热得到强化。并且，随纳米粒子体积浓度的增大，纳米流体热导率提高的同时比热容减小，总体上提高了热扩散率，纳米粒子布朗运动增强，在泡沫金属区域内流体的扰动性随之增大，使流体在泡沫金属区域内换热强度及换热速率增大，导热性能增加。

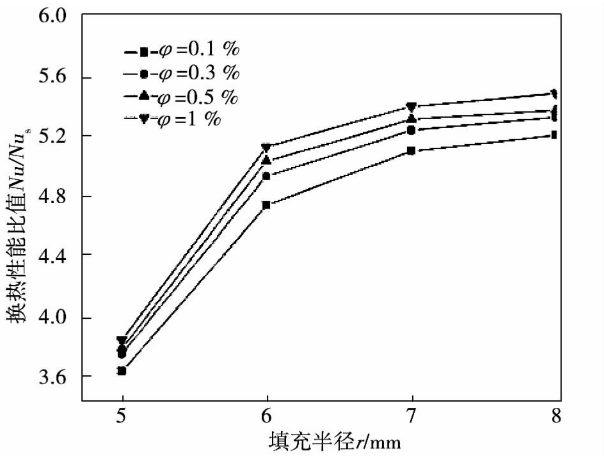

图10　纳米流体浓度与换热性能的关系

Fig. 10 Relationship between the nanofluid concentration and the heat exchange performance

2.8　纳米流体浓度与阻力系数的关系

图11表示不同体积分数纳米流体与阻力系数的关系。阻力系数随纳米流体体积分数的增大而增大，当纳米流体体积分数由0.1%提高到1%时所对应的阻力系数与基液的阻力系数相比最大升高幅度分别为19.17%、21.88%和23.60%。这是由于纳米流体黏度随体积分数增加而增大，纳米流体黏度的增加一定程度上阻碍了纳米颗粒的运动，使得热边界层厚度增大，阻力系数增加，但是所引起的阻力系数增加幅度并不大。

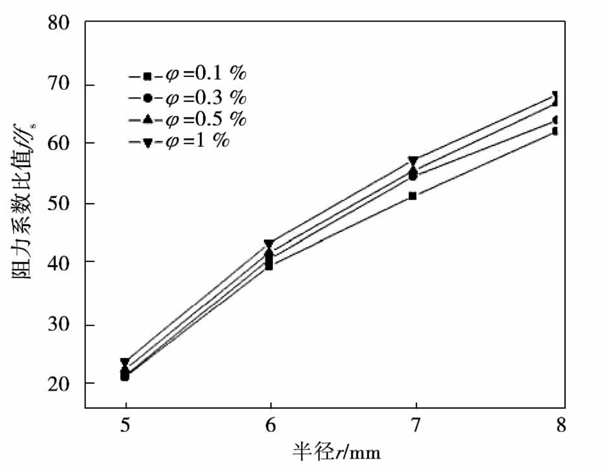

图11　纳米流体浓度与阻力系数的关系

Fig. 11 Relationship between the nanofluid concentration and the resistance coefficient

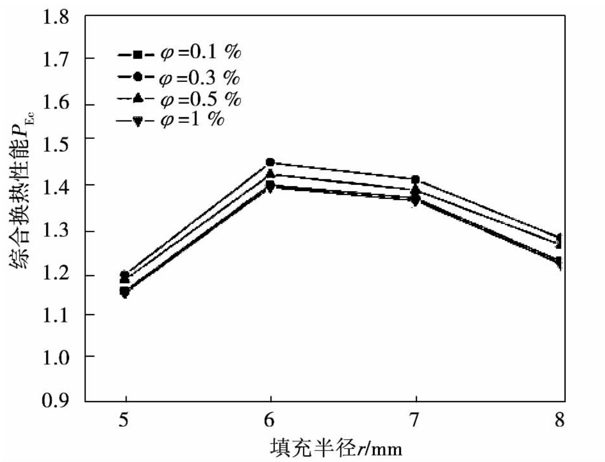

图12　纳米流体浓度与综合换热性能的关系

Fig. 12 Relationship between the nanofluid concentration and the comprehensive heat exchange performance

2.9　纳米流体浓度与综合换热性能的关系

图 12 表示纳米流体浓度与综合换热性能 P_{EC} 的关系。当填充半径厚度大于 6 mm 时，努塞尔数 Nu 的增长速率小于阻力系数 f 的增长速率，P_{EC} 值下降，但总体上所有 P_{EC} 值大于 1，即优于普通基液在泡沫金属管内的综合换热性能，表明纳米流体优良的换热特性一定程度上抵消了泡沫金属压降高的缺点。其中体积分数为 0.3% 的纳米流体的整体 P_{EC} 值最高，较 0.1%、0.5% 和 1% 纳米流体的 P_{EC} 值平均高出 3.66%、1.14%、2.83%，其中由于体积分数为 1% 的纳米流体粘度最高导致其阻力系数最大，因此其综合换热性能反而比 0.5% 的低。

3　结　论

(1) 纳米流体在填充泡沫金属管内可以起到显著增强换热的效果，并且随纳米流体浓度的增大，换热效果越好，较高浓度的纳米流体在填充泡沫金属管中的流动阻力增幅并不大;

(2) 填充半径不变，换热系数随雷诺数 Re 增大而增强: 在 $400 < Re < 1\ 200$ 范围内，P_{EC} 逐渐增大; 而在 $1\ 200 < Re < 2\ 000$ 范围，由于流体惯性及壁面剪切力所引起压降增幅明显导致 P_{EC} 值降低，当雷诺数一定时，流动阻力主要受泡沫金属区域惯性及达西数影响，即随填充半径的增大而增大;

(3) 当换热介质为 $Al_2O_3 - H_2O$ 纳米流体时，换热系数均比水的高，且随体积分数和 Re 增大换热效果增强，当 $Al_2O_3 - H_2O$ 纳米流体体积分数为 1% 时，由于粘度最大，流经相同换热管所导致流动阻力最大，其 P_{EC} 值并没有有效提升。所研究范围内当 Re 数为 1 200，纳米流体体积浓度为 0.3%，填充半径厚度为 6 mm 时可获得最大的 P_{EC} 值。

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（刘　瑶　编辑）

城镇污泥干化焚烧处置技术与工艺简介 = Brief Introduction of the Urban Sludge Drying Incineration Disposal Technology and Its Process [刊,汉] /WEN Zhe,WANG Bo,FENG Rong (College of Energy Source and Power Engineering,Shanghai University of Science and Technology,Shanghai,China,Post Code: 200093),XU Fang-qian (Shanghai Ruixin Glass Technology and Equipment Engineering Co. Ltd.,Shanghai,China,Post Code: 200120) //Journal of Engineering for Thermal Energy & Power. -2016,31(9). -1~8

Described were the basic characteristics of sludge and compared were also the working principles as well as the merits and demerits of the direct heat drying,indirect heat drying,direct-indirect combined heat drying and other sludge drying technologies. In this connection,the process roads,applications and design features of the single ininceration,diluted and mixed combustion in utility boilers,diluted and mixed combustion in waste incinerators and in cement kilns were discussed as the emphasis. It has been known from the analytic results that the sludge drying technologies are diversal and both drying sludge by using flue gases or steam are feasible. The dried sludge single incineration,diluted and mixed combustion in utility boilers or cooperative disposal in cement kilns all have their own successful examples and a proper process should be chosen according to the concrete conditions. Among all above-mentioned,the single incineration of dried sludge in a fluidized bed incinerator or diluted and mixed combustion in a utility boiler is regared as the most promising technical route. However,the sludge transmission,development of a high efficiency drying technology and equipment items as well as the processing of stinky gases in a plant territory etc. are deemed as the problems to be studied in the near future. **Key words:** solid waste,sludge disposal,drying,incineration

纳米流体在泡沫金属管内强化换热的数值模拟 = Numerical Simulation of the Intensified Heat Exchange of a Nano-fluid inside a Foam Metal Tube [刊,汉] /SUN Bin,LIU Yang (College of Energy Source and Power Engineering,Northeast University of Electric Power,Jilin,China,Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2016,31(9). -9~14

To achieve the aim of enhancing the heat exchange,the foam metal materials at various radia were inserted into the core area inside a tube and the nano-particles were also added to the basic solution. Through comparing the temperature and velocity fields inside a foam metal tube and a bare tube and analyzing the effect of the foam metal materials on the enhancement of the heat exchange,the influence of the foam metal filling ratio and the nano-fluid on the flow and heat exchange performance was studied. It has been found that the simulation results are in good agreement with the test ones given in the literatures,to fill the foam metal materials in the core area inside the tube can enhance the heat exchange performance and to add the nanofluid can improve the heat exchange effectiveness. Under the condition of a low flow speed,the heat exchange effectiveness will become better and better with an increase of the filling ratio and the concentration of the nanofluid,however,there exists an optimum matching between the foam metal filling ratio and the volumetric fraction of the nanofluid. In the range under investigation,when the filling depth is 6 mm and the volumetric fraction of the nanofluid is 0.3%,the comprehensive heat exchange performance is regarded as the optimum. To increase the flow speed and the filling ratio can contribute to enhancing the heat ex-

change, however, the pressure drop will also increase accordingly. **Key words:** foam metal, nano-fluid, intensified heat exchange, numerical simulation

横纹槽管内插断续扭带复合强化传热的实验研究 = Experimental Study of the Complex Intensified Heat Transfer by Intermittently Inserting Twisted Strips into a Transversely Slotted Tube [刊, 汉] /LEI Shi-yi, GUO Ya-jun (College of Environmental and Municipal Engineering, Xi'an University of Architectural Science and Technology, Xi'an, China, Post Code: 710055), GUI Miao, BI Qin-cheng (National Key Laboratory on Multi-phase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. -2016, 31(9). -15 ~ 19

An experiment was performed with a heat-conduction oil serving as the working medium. In a range of the Re number between the laminar flows and transition flows ($Re < 7000$), the flow and intensified heat exchange characteristics of a transversely slotted tube internally inserted with intermittent twisted strips in three different specifications and continuous twisted strips at the same twist rate ($Y = 4.13$) were investigated. Experimental coorelation formulae of the resistance coefficient and the Nu number were obtained respectively by performing a regressive analysis of the test data, thus offering a theoretical basis for calculating the complex intensified heat transfer. It has been found that the comprehensive heat exchange performance of a transversely slotted tube internally inserted with the twisted strips is superior to that of a bare tube internally inserted with the same twisted strips. The comprehensive heat exchange performance of a transversely slotted tube internally inserted with the intermittent twisted strips in a length of 66 mm is superior to that internally inserted with the continuous twisted strips. The test results can provide a theoretical basis for the reconstruction of heat exchangers and design of novel heat exchangers. **Key words:** transversely slotted tube, intermittently twisted strip, complex intensified heat transfer, performance evaluation coefficient (PEC), resistance characteristics

热管换热器内部流动与换热的数值模拟 = Numerical Simulation of the Flow and Heat Exchange Inside a Heat Pipe Heat Exchanger [刊, 汉] /XU Hong-bao, SUN Tie, YANG Xue-feng (College of Mechanical Engineering, Liaoning Petroleum and Chemical Engineering University, Fushun, China, Post Code: 113001) //Journal of Engineering for Thermal Energy & Power. -2016, 31(9). -20 ~ 26

There exists a poor flow and insufficient heat exchange of the fluid at the structural center of the fin in a single helically finned heat pipe tube bundle. As a result, the single helical fin structure was replaced by the novel dual helical fin structure and the flow field and temperature field after the improvement were simulated and analyzed by using the software Fluent. It has been found that when $Re = 500 \sim 6\,500$, compared with a heat pipe not installed with fins, the heat quantity exchanged by a heat pipe additionally installed with single helical fins will enhance by 33% to 51% and the friction resistance coefficient will increase by 6% to 24% while the heat quantity exchanged by a heat pipe additionally installed with the dual helical fins will enhance by 69% to 84% and the friction resistance