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骨架发热多孔介质通道内单相流阻力与换热特性数值模拟

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摘　要：以 Fluent6.3为平台，采用局部非热平衡模型，对紊流及紊流过渡区范围内骨架发热多孔介质竖直通道内的非达西强制对流换热进行了数值模拟。采用三维 N－S方程及标准 k－ε湍流模型描述多孔介质内的流动，详细研究了孔隙有效雷诺数 Re(400＜Re＜2000)，表面热流密度 q(q＝5.30和 90 kW/m²)和冷却剂入口温度 T_{in}(T_{in}＝20、50和 80 ℃)的变化对多孔介质流道内流动阻力及换热特性的影响。结果表明：低热流密度下，表面热流密度的变化对流动阻力和换热系数的影响很小；小球直径对换热系数的影响显著，且随着雷诺数的增加而增加；换热系数随冷却剂入口温度的增加而减小。

关　键　词：骨架发热；多孔介质；强制对流换热；局部换热；数值模拟

中图分类号：TK124　　　文献标识码：A

引　言

骨架发热多孔介质内流体的流动与换热研究在工程中有很广泛的应用背景，如核反应堆堆芯元件的设计与安全运行、核废料的安全存放、小球堆积床中的放热等[1]。

已有不少文献对骨架发热多孔介质内的流动与换热进行了相关的研究和报道，但这些研究多数都采用了局部热平衡假设[2~6]，即假设在多孔介质内的任何位置固体骨架和流体的温度相等。这样处理可以使模型得到简化，但当多孔介质内固体骨架与流动介质之间的温度差较大时，采用局部热平衡假设是不合理的。目前，在公开文献中对骨架发热多孔介质内的自然对流换热研究较多[2~5]，而对骨架发热多孔介质内强制对流换热的研究较少。

本研究以 Fluent6.3为平台，采用局部非热平衡模型，对骨架发热多孔介质竖直流道内的强制对流换热进行了数值模拟，详细分析了孔隙有效雷诺数，热流密度和冷却剂入口温度对多孔介质通道内流动阻力和局部换热特性的影响。

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1　数值模型

使用 Gambit构建文献[7]中无量纲直径 D＝0.16和 0.1的多孔介质通道模型，如图 1所示，其中 $D=d_s/d$，d为多孔介质通道内径，d_s为小球直径。边界条件的设定及网格划分方案等细节参考文献[8]。

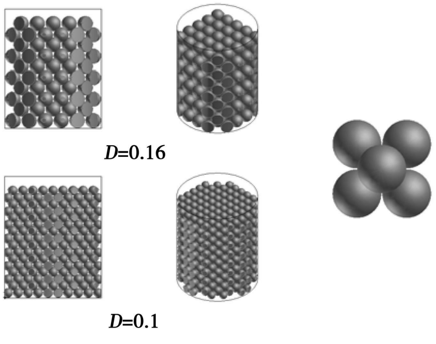

图 1　通道内小球分布示意图

假设通道内充满各向同性、均匀的饱和多孔介质和水；多孔介质固体骨架产生均匀分布的热源，其表面热流密度为 q(W/m²)；骨架相的材料为不锈钢，物性参数为常数；管道入口处流体的速度和温度分别为 u_{in}和 T_{in}，流体项的物性参数使用阶梯函数表示；管壁为恒温冷面，壁面温度与流体入口温度相同。采用 N－S方程来描述多孔介质通道内的流动，同时引入局部非热平衡模型(即双能量方程模型)来考虑多孔介质内骨架与流体间的换热。其控制方程为：

连续方程：

$$\nabla \vec{V}=0 \tag{1}$$

动量方程：

$$\rho \vec{V}\cdot \nabla \vec{V}=\mu \nabla^2 \vec{V}-\nabla P+\rho g \tag{2}$$

流体相能量方程:

$$\rho_f c_p u \nabla T_f = \varphi \nabla k_f \nabla T_f + \varphi q' + h(T_f - T_s) \quad (3)$$

骨架相能量方程:

$$0 = \nabla \cdot (k_s \nabla T_s) + q'_s + h(T_f - T_s)/(1-\varphi) \quad (4)$$

式中: V—流体在孔隙内的真实流速, $V = u/\varphi$; φ—孔隙率; u—平均表观流速; ρ—流体密度; μ—动力粘度; c_s—固体的比热, c_p—流体的定压比热, k—导热系数; q'—内热源产生的单位体积的热量, W/m³; h—对流换热系数。下标 f, s—流体相和固体相。

边界条件为:

$$u_0 = v_0 = 0,\ w_0 = |u|,\ T_0 = T_{in} \quad (Z=0)$$

$$P = P_{out} \quad (Z=L) \quad (5)$$

在相同求解条件下比较网格疏密对计算结果的影响, 经网格无关性验证后, 确定网格划分方案。采用标准 $k-\varepsilon$ 湍流计算模型, 壁面采用无滑移模型, 用标准壁面方程 (standard wall functions) 对壁面进行处理, 求解格式采用二阶迎风格式。

2　计算结果分析

研究了孔隙有效雷诺数, 热流密度和冷却剂入口温度对多孔介质通道内流动阻力和局部换热特性的影响, 计算中取 $400 < Re < 2000$, 骨架的表面热流密度 $q = 5$、30和 90 kW/m²; 冷却剂入口温度 $T_{in} =$ 20、50和 80 ℃。多孔介质通道内流体流动的雷诺数 (孔隙有效雷诺数) 定义为: $Re = 2\rho u d_s / 3\mu(1-\varphi)$。

2.1　模拟方法验证

首先进行模拟方法的验证, 对文献 [9] 中多孔介质通道内的强制对流换热问题进行数值计算。从图 2可以看出, 模型的计算值与实验值的最大误差为 10%, 验证了模型的准确性和可靠性。

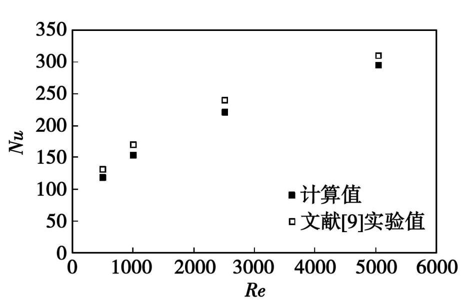

图 2　平均 Nu计算值与文献 [9] 实验值的对比

2.2　内热源对多孔介质通道内流动阻力的影响

图 3为表面热流密度不同时, 两种多孔介质通道内的阻力系数随 Re数的变化趋势。

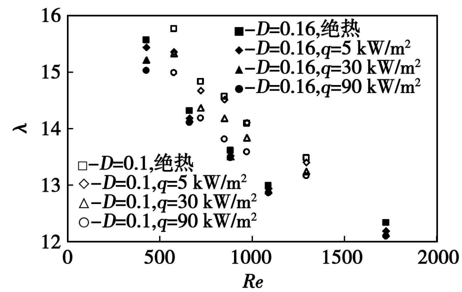

图 3　热流密度对流动阻力的影响

从图 3中可以看出, 随着表面热流密度的增加, 两种通道的阻力系数没有明显减小。这是因为, 在热流密度相对较小时, 流体的物性参数变化不大, 而物性参数的变化主要影响粘性阻力系数的变化, 对于惯性阻力系数的影响相对较小。在本研究的雷诺数范围内, 流体的流动处于紊流及紊流过渡区, 惯性阻力的影响效果远远大于粘性阻力, 因此, 在热流密度较小时, 表面热流密度的变化对通道的阻力系数变化影响很小。

2.3　热流密度及小球直径对换热特性的影响

不同表面热流密度下, 两种小球的平均换热系数随 Re的变化趋势如图 4所示。随着表面热流密度的增加, 两种小球的平均换热系数没有明显增加, 这是因为当热流密度增加时, 加热小球表面温度也随之升高, 且升高的幅度大于流体出口温度升高的幅度, 从而使得加热小球的平均壁面温度与流体进出口平均温度的差值增大, 因此换热能力没有明显增加。

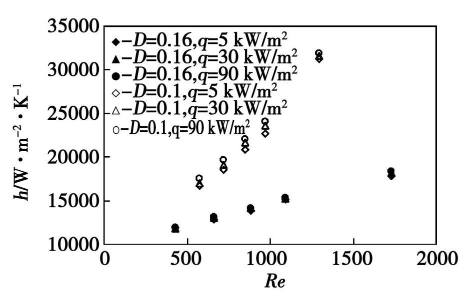

图 4　表面热流密度对平均换热系数的影响

另外, 从图 4中可以看出, D=0.1的多孔介质通道的换热能力明显高于 D=0.16的多孔介质通道, 并且换热能力的增幅随着雷诺数的增加也在增长, 在本研究范围内最小增幅约为 40%, 最大增幅

约为 95 %。这是由于流体在由小球堆积而成的多孔介质中换热时，影响换热的因素除流速及固体骨架和流体的导热系数之比以外，还包括边壁效应和热弥散效应，而这两者又与固体小球直径的大小有着密切的联系。

在多孔介质通道内，由固相形成的孔隙具有弯曲性、无定向性和随机性等特点，热弥散效应使得多孔结构中的换热过程极其复杂。现有研究表明，热弥散效应能够强化多孔介质中的换热，特别是在低雷诺数下，强化效果更明显，且热弥散效应随着小球直径的增加而增强。但由于靠近壁面处的孔隙率远远大于平均孔隙率，从而减弱了热弥散效应。当管内填充小球的直径增大到一定程度，孔隙率较大的边壁区占整个流动区域空间的份额较大时，边壁效应的影响逐渐增大到足以抵消热弥散效应，此时，填充小球直径进一步增大反而会降低换热效果。同时，随着小球直径的减小，小球与流体之间的接触面积增大，流体从发热小球表面带出的热流也随之增加，从而减小了发热小球表面与流体之间的平均温差，增强了小球与流体间的对流换热。

因此，在小球填充多孔介质中，小球直径对换热能力的影响主要是由于流速、边壁效应和热弥散效应共同耦合作用的结果。

2.4 冷却剂入口温度对换热特性的影响

图 5为冷却剂入口温度不同时，发热小球表面的平均换热系数随 Re数的变化趋势。

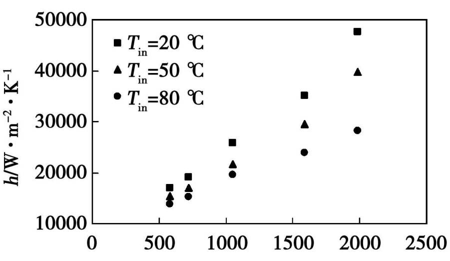

图 5 冷却剂入口温度对平均换热系数的影响
（D=0.1，q=30 kW/m^2，工作压力 2 MPa）

从图 5中可以看出，随着冷却剂入口温度的增加，发热小球表面的平均换热系数呈下降趋势。这是由于，随着入口水温的增加，骨架相的平均温度大幅增加，而流体相的出入口温差随入口水温的增加而增加，但平均温度的增加幅度相对较小，两相之间的温差随表面热流密度的增大而增大。造成这一现象的主要原因是，水的比热随温度的升高而增加，这就使得流体相的出入口温差随流体入口温度的升高而增加。而水的导热系数随着冷却剂入口温度的增加而增加，从而使得流体相的平均温度增加；同时，随着冷却剂入口温度的增加，对流换热系数 h迅速降低，两相之间的换热显著减弱，骨架所产生的热量不能被冷却剂带出，因此骨架相的温度大幅升高，两相间的温差增大，非热平衡效应增加，最终导致低温水的换热能力强于高温水。

3 结 论

本研究以 Fluent6.3为平台，采用局部非热平衡模型，对骨架发热多孔介质竖直通道内的强制对流换热进行了数值模拟，得到了以下结论：

（1）当发热小球的热流密度较小时，流体的物性参数变化很小，流动阻力与换热系数随热流密度的增加没有明显的变化。

（2）小球填充多孔介质通道内，小球直径对换热能力的影响显著，并随雷诺数的增大而增大。

（3）随着冷却剂入口温度的增加，多孔介质通道内的换热能力呈下降的趋势。

因此，小球填充多孔介质中的换热特性的变化是流速、固体小球直径的大小及固体骨架和流体的导热系数之比等因素共同耦合的结果。

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（编辑 伟）

汽轮机功率背压特性的通用计算方法及其应用 = Universal Method for Calculating the Power/back-pressure Characteristics of a Steam Turbine and Its Applications[刊,汉] /XU Da-mao, KE Yan, WANG Shi-yong (China Guangdong Nuclear Power Group Co. Ltd., Shenzhen, China, Post Code: 518031) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —605~608

Proposed was a universal method for calculating the power/back-pressure characteristics (i. e. micro-increased capacity) of a steam turbine. The method in question boasts two big features: one is simple, it is only necessarily to know the low pressure exhaust steam area and flow rate, and another is accurate, the errors relative to the operating or test data are within a range of 0.3%. Its theory was described in detail and the errors possibly caused by various assumptions were analyzed. Key words: steam turbine, power/back-pressure characteristics, performance examination test, system optimization

水蒸气在 TA2改性表面冷凝传热特性实验研究 = Experimental Study of the Condensing and Heat Transfer Characteristics of Vapor on Pure Titanium (TA2) Denatured Surfaces[刊,汉] / QI Bao-jin, ZHANG Li, XU Hong, et al (United Nations Key Laboratory on Chemical Engineering, College of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, China, Post Code: 200237) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —609~613

Through denaturing of pure titanium (TA2) surfaces, obtained were the condensing surfaces with different static contacting angles and visualization experimentally studied were the heat transfer characteristics of vapor on surfaces of various test specimens. The test results show that the steam assumes a hybrid condensing in coexistence of both liquid droplets and rivulet liquid film on the original surfaces and a film-shaped condensing on the HF etched surfaces, thus the heat transfer performance of the latter will drop to less than 30% of that of the former. However, it assumes a conspicuous droplet-shaped condensing on the surfaces oxidated by H_2O_2 and that treated in the same way after being etched by HF. The corresponding heat transfer performance will also be enhanced significantly, approximately 1.3~1.6 times of the heat transfer performance of the original surfaces. Furthermore, the intensified condensing effectiveness of the surfaces treated in the two steps is even more conspicuous. The microscopic morphological observation and analysis of the specimen surfaces show that the microscopic morphological change of the condensing surfaces should be the main cause of the differences in the static contacting angles and condensing morphology of various specimen surfaces. Key words: surface denaturing, titanium, drop-shaped condensing, heat transfer characteristics

骨架发热多孔介质通道内单相流阻力与换热特性数值模拟 = Numerical Simulation of the Resistance and Heat Exchange Characteristics of a Single-phase Flow in the Passages of a Skeleton Heat Generation Porous Medium[刊,汉] /YU Li-zhang (Zhonghe Qingyuan Environmental Technology Engineering Co. Ltd., Beijing, China, Post Code: 100037), SUN Li-cheng, SUN Zhong-ning (College of Nuclear Science and Technology, Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —614~616

With Fluent6.3 serving as a platform, a partial heat non-equilibrium model was adopted to numerically study the non-Darcian forced convection heat exchange in the vertical passages of a skeleton heat generation porous medium in a turbulent flow zone and its transition one. Three-dimensional N—S equation and standard k—ε turbulent flow model were used to depict the flow inside the porous medium. On this basis, the influence of the change in the pore effective Reynolds number Re (400< Re< 2000), surface heat flux density q (q=5 kW/m², 30 kW/m² and 90 kW/m²) and coolant inlet temperature T_{in} (T_{in}=20 ℃, 50 ℃ and 80 ℃) on the flow resistance and heat exchange characteristics was studied in detail. The research results show that at a low heat flux density, the change of surface heat flux density has a very small influence on the flow resistance and heat exchange coefficient. However, the diameter of the small balls exercises a significant influence on the heat exchange coefficient and such an influence will increase with an increase of Reynolds number. Moreover, the heat exchange coefficient will decrease with an increase of the coolant inlet temperature. Key words: skeleton heat generation, porous medium, numerical simulation

膜式全热换热器 EHD电场强化换热的实验研究 = Experimental Study of the EHD (Electrohydrodynamics)-based Electric Field Intensified Heat Exchange of a Membrane Type Full Heat Exchanger [刊, 汉] / SUN Shu-hong, LIU Yuan-wei, LIU Guang-lin, et al (Education Ministry Key Laboratory on Heat Transfer Intensification and Process Energy Conservation, Beijing University of Technology, Beijing, China, Post Code: 100124) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (6). — 617 ~ 620

To enhance the heat exchange efficiency of a membrane type full heat exchanger, a high voltage electric field was applied to the heat exchanger. Under the same test conditions, the influence of the electric field applied from outside on the heat exchange effectiveness was analyzed by measuring both sensible and latent heat efficiency of the exchanger. On this basis, the heat exchange effectiveness of the exchanger was tested at various voltages of electric poles and different wind speeds. The test results show that the application of a high voltage electric field to the flow field of the heat exchanger can effectively enhance its sensible heat efficiency but insignificantly increase its latent heat efficiency. At a low wind speed, the intensified heat exchange effectiveness will be even more conspicuous. Key words: full heat exchanger, intensified heat exchange, electrohydrodynamics (EHD)

流化床反应器内气固两相流动特性的研究 = Investigation of the Gas-solid Two-phase Flow Characteristics Inside a Fluidized Bed Reactor [刊, 汉] / SUN Qiao-qun, ZHU Wei-bing (College of Astronautics and Architectural Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001), GAO Jian-min, LIU Hui-lin (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (6). — 621 ~ 626

By simulating the particle phase flow based on the particle kinetic theory and taking into account the two phase interaction by using the fluid and particle two phase flow theory, established was a CFD (computational fluid dynamics) model featuring the multiple phase flow inside a fluidized bed nuclear reactor, and numerically simulated and studied were the fluid kinetic behaviors in the abovementioned reactor. The calculation results show that the distribution of particle concentrations on the cross section obtained by using Gidaspow drag force model shares a compar-