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波纹通道内充分发展层流流动的简化分析

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摘 要: 对平行放置的波幅与波数不同的两块波纹板形成的通道内的定型层流流动, 以壁面波纹的波幅为小量进行摄动, 建立近似分析模型, 得到了速度分布表达式, 考察了流量和阻力系数与壁面波纹的波幅和波数之间的关系。结果表明, 流量随波纹板的波幅和波数的增大而增大, 而壁面阻力则随两块板相对波数的大小、波幅和波数呈现不同的变化。

关 键 词: 波纹通道; 层流流动; 流量; 阻力系数

中图分类号: TK124; TQ021.1 文献标识码: A

引 言

流体介质在波纹板通道内流动时, 按照设计目的的不同, 流体介质的流动方向与壁面波纹的变化方向可以垂直, 也可以平行。对这两种类型的流动和传热已经有了很多研究[1~3]。然而, 在已有的研究中, 无论介质的流动方向是平行还是垂直于波纹, 波纹壁面的几何参数都是一样的。在两块波纹板形成的二维流道内, 当上下波纹板的波纹的振幅、频率不相同时, 流动特性会有什么样的表现, 这方面的研究还鲜有报道。

为此, 对流动方向与壁面波纹的波峰波谷相平行的二维通道内充分发展的层流流体展开研究, 以壁面正弦型波纹的波幅与通道平均高度的比值为摄动参数建立简化分析模型, 对壁面不同波纹参数对流动的影响进行探索, 了解这种情况下的流量与阻力特性的变化规律。

1 模型分析

图 1为由两块表面加工有波长和波幅互不相同平行放置的正弦形状的波纹板组成的流体通道, 流体沿垂直于纸面的方向在此通道内流过。垂直纸面的方向取为 x坐标, 图上没有标出。假定流体物性恒定, 通道在 x方向足够长, 在 z方向也足够宽。在充分发展区, 流速及压力梯度沿 x方向不再变化, 在 y向和 z向的速度变为零, 流体的流动成为 x方向的一维流动, 其流动速度 u只沿 y和 z坐标发生变化。设两个波纹板的中线之间的距离 h保持不变, 上板波幅与波长分别为 B和 l_2, 下板波幅与波长分别为 A和 l_1。

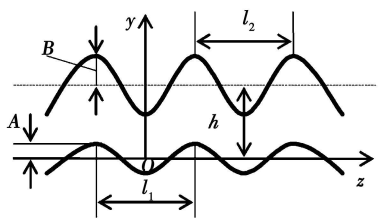

图 1 波纹板通道

1.1 无量纲控制方程

以 μ、u、p表示流体的动力粘度、x方向的速度、流体的压力, 设在 y和 z平面沿 z方向单位长度上, 在上下板没有波纹时的介质的体积流量为 q_0, 再以两板间距 h为特征长度、q_0/h为特征速度、$\mu q_0/h^2$为特征压力, 将坐标、速度、压力无量纲化, 以各量的大写表示。在波纹板情况下, 假定 $A/h=\varepsilon$为一小量, $B/h=k\varepsilon$, k为数量级为 1的波纹振幅系数。设 $\lambda_1=2\pi h/l_1$, $\lambda_2=2\pi h/l_2$, 则流动控制方程及边界条件为:

$$\frac{\partial U}{\partial X}=0 \tag{1}$$

$$\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}-\frac{\partial P}{\partial X}=0 \tag{2}$$

$$Y_1=\varepsilon\cos(\lambda_1 Z),\ U=0 \tag{3}$$

$$Y_2=1+k\varepsilon\cos(\lambda_2 Z),\ U=0 \tag{4}$$

1.2 近似方法

将无量纲流速展开:

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$$U(Y,Z)=U_0(Y)+\varepsilon U_1(Y,Z)+\varepsilon^2 U_2(Y,Z)+\cdots \tag{5}$$

由于垂直于流动方向的横截面的大小和方向都恒定不变,因而沿流动方向即 x方向的压力梯度也恒定不变。将式(5)代入式(1)~式(4),按近似等级展开微分方程,将边界条件按泰勒级数展开,转换到 $Y=0$和 $Y=1$处。取一级近似,分别得零级和一级近似方程组:

$$U_{0YY}-P_X=0 \tag{6}$$

$$U_0(0,Z)=0,\ U_0(1,Z)=0 \tag{7}$$

及:

$$U_{1YY}+U_{1ZZ}=0 \tag{8}$$

$$U_1(0,Z)+\cos(\lambda_1 Z)U_{0Y}(0,Z)=0$$

$$U_1(1,Z)+k\cos(\lambda_2 Z)U_{0Y}(1,Z)=0 \tag{9}$$

式中:脚标中的第一个数字表示零级或一级近似速度;第二位及后边的字母表示对 Y或 Z坐标求一阶或二阶偏导。

2 结果及讨论

2.1 方程的求解

由式(6)和式(7)可得:

$$U_0=\frac{1}{2}P_X(Y-Y^2) \tag{10}$$

对一级方程组,首先将式(10)代入式(9),然后设一级流速为:

$$U_1(Y,Z)=F_1(Y)\cos(\lambda_1 Z)+F_2(Y)\cos(\lambda_2 Z) \tag{11}$$

则,对 Y、Z坐标的二阶偏导为:

$$\begin{aligned}U_{1YY}&=F''_1\cos(\lambda_1 Z)+F''_2\cos(\lambda_2 Z)\\U_{1ZZ}&=-\lambda_1^2F_1\cos(\lambda_1 Z)-\lambda_2^2F_2\cos(\lambda_2 Z)\end{aligned} \tag{12}$$

其中,以在变量右上角加“′”表示该变量对 Y坐标求导。将式(12)代入式(8),然后根据方程特点及边界条件可得关于 F_1和 F_2的方程组:

$$\begin{aligned}&F''_1-\lambda_1^2F_1=0\\&F_1(0)=-\frac{1}{2}P_X,\ F_1(1)=0\\&\text{及}\\&F''_2-\lambda_2^2F_2=0\\&F_2(0)=0,\ F_2(1)=\frac{1}{2}kP_X\end{aligned} \tag{13}$$

解出 F_1和 F_2后,代入式(11)可得 U_1,代入式(5)可得一级近似的总流速为:

$$U\approx U_0+\varepsilon U_1=\frac{1}{2}P_X(Y-Y^2)+\frac{1}{2}\varepsilon P_X\times\left[\frac{\mathrm{sh}\lambda_1(Y-1)\cos(\lambda_1 Z)}{\mathrm{sh}\lambda_1}+\frac{k\,\mathrm{sh}\lambda_2 Y\cos(\lambda_2 Z)}{\mathrm{sh}\lambda_2}\right] \tag{14}$$

以波数较小的板上的波纹在 Z方向发生一个周期变化的通道范围内单位时间流过的流体的体积考察流量的变化关系,取 $Z_1=0$,$Z_2=l_{min}/H=L_{min}$,l_{min}为 l_1和 l_2中的较小者,则沿 Z坐标单位长度上的有量纲流量及无量纲流量形式为:

$$q=\frac{1}{l_{min}}\int_{z_1}^{z_2}\int_{y_1}^{y_2}u\,dy\,dz=q_0\frac{h}{l_{min}}\int_{Z_1}^{Z_2}\int_{Y_1}^{Y_2}U\,dY\,dZ$$

$$Q=q/q_0=\frac{h}{l_{min}}\int_{Z_1}^{Z_2}\int_{Y_1}^{Y_2}U\,dY\,dZ=\frac{1}{L_{min}}\int_{Z_1}^{Z_2}\int_{Y_1}^{Y_2}U\,dY\,dZ \tag{15}$$

在波纹板单位面积上的剪切力 τ_w为:

$$\begin{aligned}\tau_w&=\mu\frac{\partial u}{\partial n}\Big|_w=\mu\sqrt{(\partial u/\partial y)^2+(\partial u/\partial z)^2}\Big|_w\\&=\frac{\mu q_0}{h^2}\sqrt{(\partial U/\partial Y)^2+(\partial U/\partial Z)^2}\Big|_w\\&=\rho u_m^2\frac{1}{Q\,Re}\sqrt{(\partial U/\partial Y)^2+(\partial U/\partial Z)^2}\Big|_w\end{aligned} \tag{16}$$

式中:n—波纹板的法线方向;ρ—流体密度;u_m—流体在通道内的平均流速;Re—雷诺数,$Re=u_m h/\nu$。于是,流阻系数 C_f为:

$$C_fRe=\frac{2}{Q}\sqrt{(\partial U/\partial Y)^2+(\partial U/\partial Z)^2}\Big|_w \tag{17}$$

2.2 速度和压力的特点

本研究的模型是无量纲形式的,因此针对一个具体工况,要了解其实际的速度分布及流量,在由式(14)和式(15)得到波纹板通道内的无量纲速度和流量后,还需要求得对应间距 h的平行平板通道在相同的压力差 Δp下,沿 z方向单位长度的截面通道的流量 q_0。由式(14)可得实际速度分布 $u=Uq_0/h$及流量 $q=Qq_0$。

而波纹通道横截面上的压力在充分发展、不计重力的条件下,是恒定不变的,其有量纲形式与无量纲形式之间的关系为 $p=P\mu q_0/h^2$。压力只在流动方向上发生等速率的降低,是一个参变量。

2.3 结果讨论

2.3.1 流量分析

在本研究中,影响波纹通道内的流量和壁面摩擦阻力的因素是压力梯度 P_X以及反映流道几何特点的波纹无量纲振幅 ε、上板的波纹振幅系数 k、下板的波数 λ_1和上板的波数 λ_2等参数。为便于比较,也将平行平板通道内的流动特性一同绘于图上。

以无量纲形式的流量与压力梯度之比为纵坐标、以波纹板的无量纲波幅为横坐标,绘出流量与波纹通道几何参数之间的变化关系,如图 2~图 4所

示。由图可知，在相同的工况下，波纹通道内的流量都大于平行平板通道内的流量，且随波纹通道几何参数 ε、k、λ_1、λ_2 的增大而增大，当 ε 趋于零时，各工况下的流量都趋近于平行平板。说明，当波纹通道横截面偏离矩形的程度增大时，平均流速增大使流量也随之增大。

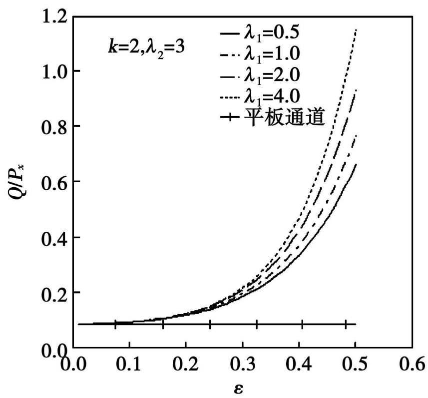


图 2　下板波数对流量的影响

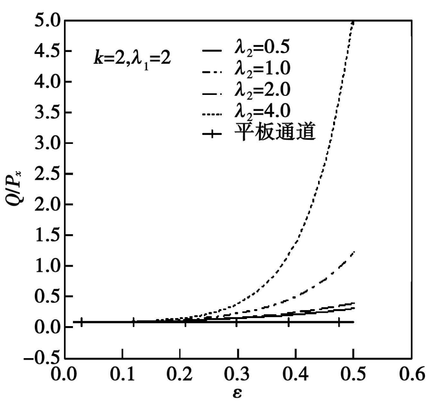


图 3　上板波数对流量的影响

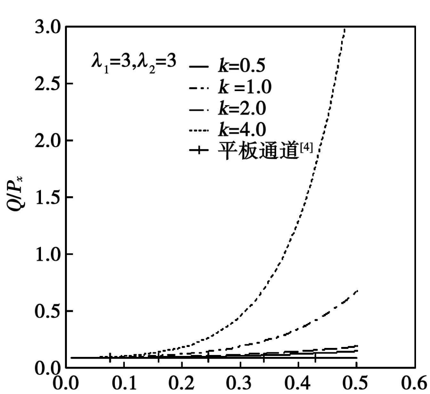


图 4　上板波纹系数对流量的影响

2.3.2　阻力系数分析

在平行平板通道充分发展的层流流动中，壁面上的摩擦阻力系数处处恒定不变。当通道壁面为波纹形状时，阻力系数沿壁面各处变化。当上下两块波纹板的波幅和波数不同时，阻力系数在壁面上的分布更加复杂。以波纹通道的无量纲 Z坐标为横坐标、以阻力系数和雷诺数的乘积为纵坐标，在阻力特性变化的一个周期内，绘出了上下两板的阻力特性在不同波纹参数下沿 Z坐标的分布，如图 5 ~图 7 所示，图上同时也绘出了平行平板的阻力特性。由图可知，阻力系数在波纹板壁面上，沿宽度方向即沿 Z坐标的分布呈现出波动的形式，其波峰波谷及其间隔疏密都随波纹板几何参数的不同组合而增大减小，参差变化。在相同的几何参数下，上下板上的阻力系数随几何参数的变化也显示出不同的变化趋势。

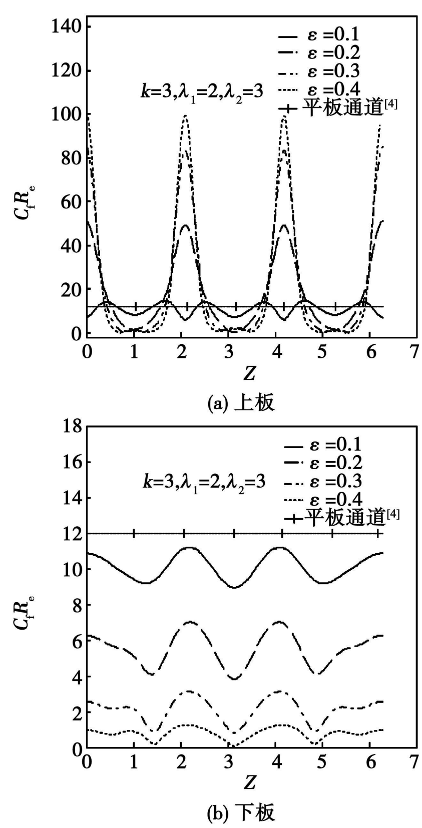
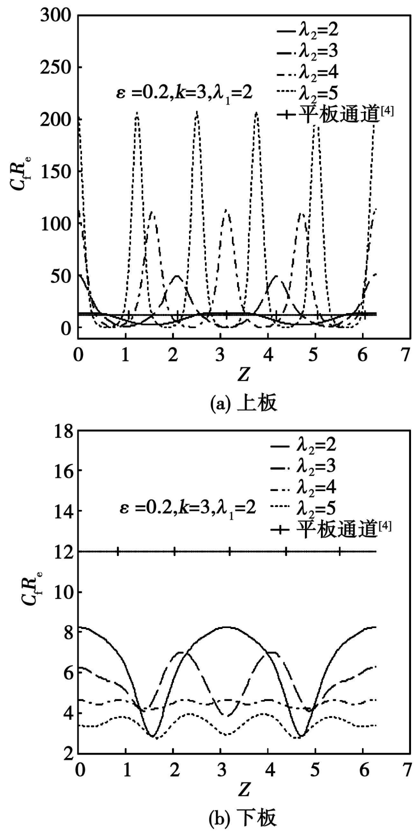


图 5　波幅对阻力系数的影响

图 5和图 6显示，当两个板的波纹振幅同时增大，以及当上板的波纹密度加大时，上板的阻力系数沿各处的波动及其平均值都随之增大，而下板上的阻力系数曲线下移，波动减小，平均值降低。这说明在这种情况下，沿上板法线方向的速度梯度增大，波

动加剧,而沿下板法线方向的速度梯度减小,波动减弱。由图 6可知,当上板的波纹密度增大时,上下板上的阻力波动的频率也增大,这是因为板上波纹密度增大,流体速度变化的频率也自然增大。由图 7可知,在下板波纹不变、而上板波幅增大时,上板阻力系数的波动幅度增大,但其平均值减小;下板上的阻力系数曲线下移,平均值降低,而波动幅度增大,反映出仅仅一个板上的波纹振幅增大时引起的速度梯度有不同的变化。图 5 ~图 7所选工况,都以上板的波数大于下板的波数为例,如果下板的波数大于上板的波数,则两个板上的阻力特性的变化只是调换一下对象,具体规律不变。

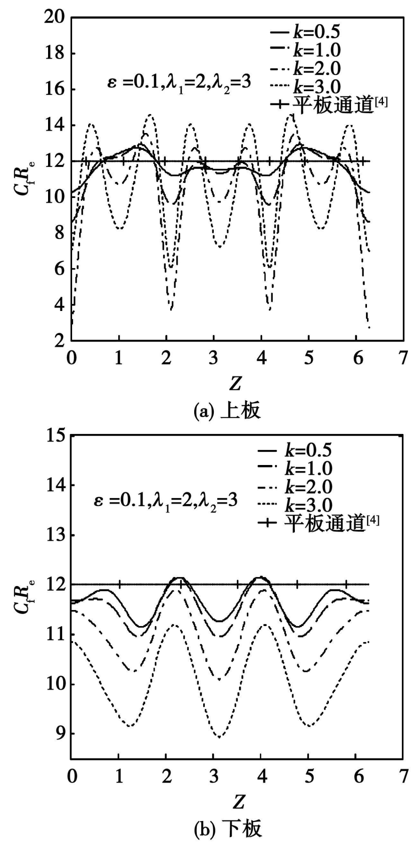


(a) 上板　(b) 下板

图 6　波数对阻力系数的影响

3 结　论

采用摄动展开法研究了正弦波纹、波纹的波幅与通道平均高度之比为小量、水平放置的平行波纹板通道内的充分发展的层流流动。得到了流动速度与各影响因素之间的关系表达式,分析了流量和壁面阻力系数与壁面几何参数之间的变化关系。研究表明,上下两块波纹板的波纹对通道内的流量有相同的影响,流量随两板的波幅和波数的增大而增大。而两个板面上的阻力特性则表现出相反的趋势。当板面上的波数是较大者时,该板上的阻力系数随该板的波幅和波数的增大而增大,当板面上的波数是较小者时,阻力系数则随该板的波幅和波数的增大而减小。阻力系数在两个板面上呈现出周期性的变化,此周期与板面波纹的周期不同。



(a) 上板　(b) 下板

图 7　波幅系数对阻力系数的影响

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介质特性对脱硫浆液循环泵性能影响的数值分析 = Numerical Analysis of the Influence of the Medium Characteristics on the Performance of a Desulfurization Slurry Circulating Pump[刊, 汉] / WANG Shu-dong, HU San-gao, CAO Rui, et al (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. —2010, 25(6). —657 ~662

By using numerical calculation software Fluent 6.2, which is based on the philosophy of computational fluid dynamics, and on the basis of choosing a rational multiphase flow model and control equation, numerically simulated was the flow field inside a hybrid flow type desulfurization slurry circulating pump in a 300 MW thermal power plant. The influence of such medium characteristics as particle diameter, solid phase volumetric points and slurry density etc. on the pump performance was studied. Then, a mechanism analysis was conducted of such phenomena as poor hydraulic performance and serious abrasion of the flow path components etc. existing in the practical operation of the desulfurization slurry circulating pump due to the particularity of the medium in hoping to provide reference for improving the theory of the pump under discussion and for its practical modification and operation in thermal power plants. Key words: desulfurization slurry circulating pump, medium characteristics, multiphase flow, numerical simulation, hydrodynamic performance

基于 QFT的加热炉温度控制系统的设计与仿真 = Design and Simulation of a Temperature Control System for a Heating Furnace Based on the Quantitative Feedback Theory[刊, 汉] / ZUO Wei-heng, WANG Yan (National Key Laboratory on Power Transmission and Distribution Equipment, System Safety and New Technology, Chongqing University, Chongqing, China, Post Code: 400030) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). — 663 ~667

The temperature control system for heating furnaces is characterized by such features as a big inertia, a long delay and time variation etc. It is difficult to achieve satisfactory control effectiveness for a temperature control system by adopting the conventional control methods. By making use of respective advantages of the quantitative feedback theory, fuzzy control and traditional PID (proportional, integral and differential) control, a controller was designed. The simulation results show that the controller being designed can solve very well the robust design problem of the control system resulting from the uncertainty of the parameters of the control system for the heating furnace and can also obtain satisfactory dynamic and static control characteristics in compliance with the requirement for changes of operating conditions of the object under control. Key words: QFT (quantitative feedback theory), heating furnace, fuzzy control, robust control, PID (proportional, integral and differential), uncertainty system

波纹通道内充分发展层流流动的简化分析 = Simplified Analysis of the Laminar Flow Fully Developed Inside the Corrugated Passages[刊, 汉] / SHI Jin-sheng (College of Mechanical Engineering, Tianjin University of Science and Technology, Tianjin, China, Post Code: 300222) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —668 ~671

Perturbed was the fixed type laminar flow in the passages formed by two corrugated plates having different amplitudes and number of waves placed in parallel with the amplitude of the wall surface waves serving as the small value and established was an approximate analytic model. On this basis, a velocity distribution expression was obtained and the relationship between the flow rate and the drag force coefficient as well as between the amplitude and number of the wall surface waves was investigated. It has been found that the flow rate will increase with an increase of the amplitude and wave number while the drag force of the wall surface will change differently with the magnitude of the relative wave number of the two plates and their amplitude as well as wave number. Key words: corrugated passage, laminar flow, flow rate, resistance coefficient

固体氧化物燃料电池—燃气轮机混合动力系统的热力学分析 = Thermodynamic Analysis of a Solid Oxide Fuel Cell-Gas Turbine Hybrid Power System[刊，汉] / LI Yang, WENG Yi-wu, ZHAO Zhen-ke (Education Ministry Key Laboratory on Power Machinery and Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —672~676

With a bottom layer solid oxide fuel cell-gas turbine hybrid power system (SOFC-GT) serving as the object of study, established was a modularization simulation model and verified was the model in question by utilizing the test data. By making use of the model, the thermodynamic performance of the system and its major components was studied with various coal gases and biomass gas serving as the fuel and the influence of fuel constituents on the system performance was analyzed. The research results show that the CH_4 and CO content of the fuel exercise a relatively big influence on the system performance. Although the efficiency of the solid oxide fuel cells is far higher than that of conventional heat engines, they are still the components in the system having a maximum exergy loss. Key words: solid oxide fuel cell, biomass gas, fuel cell-gas turbine hybrid power cycle, syngas

城市污水污泥热解特性及动力学研究 = Pyrolysis Characteristics and Kinetic Study of Urban Sewage Water and Sludge[刊，汉] / LIU Xiu-ru (Postgraduate College, Chinese Academy of Sciences, Beijing, China, Post Code: 100190), LIU Qing-gang, ZHAO Ke (Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(6). —677~680

An experiment was made of the urban sewage water and sludge by using a thermogravimetric analyzer and a Fourier infrared spectrum device, and its reaction process and gas products released were observed. In this connection, the solutions to the pyrolysis apparent kinetic parameters were sought. It has been found that the pyrolysis, gasification and combustion reactions occurring to the sludge sample in the N_2、CO_2 and N_2+O_2 atmosphere have different characteristic parameters in the reaction processes. The main pyrolysis temperatures in the N_2 atmosphere range from 200 to 560 ℃ and the reaction process basically comes to an end at 600 ℃. With an increase of the temperature rise speed, the maximum pyrolysis weight loss speed will increase. The pyrolysis process of the sludge sample in the N_2 atmosphere will separate out H_2O, CO_2, CH_4 and CO in turn. Different reaction phases in the pyrolysis process of the sludge sample have different reaction mechanisms and kinetic parameters and the apparent activation energy is within a range from 60 to 100 kJ/mol. Key words: sludge, pyrolysis, thermogravimetric analysis, atmosphere, temperature rise rate, apparent kinetics