模拟与计算

文章编号: 1001－2060(1999)06－0465－02

稠密气固两相流的直接数值模拟

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摘　要: 分别用欧拉方法处理气相场和用拉格朗日方法处理离散颗粒场。在处理颗粒场时考虑到颗粒直径、比重、材料的刚度、摩擦系数等对颗粒运动的影响。用直接模拟法分别对漏斗流、球磨机以及喷动流化床内颗粒的运动进行了模拟,并通过实验对喷动流化床的模拟结果进行了验证。

关　键　词: 流化床; 气固两相流动; 直接数值模拟

中图分类号: TK229.66

在工业实际中存在着许多稠密的气固两相流动,例如鼓泡流化床中的气固流动,其特点是床内颗粒分布极不均匀,存在着气泡和相互密集接触的颗粒群,颗粒间存在着激烈的碰撞与摩擦,这些因素对气固流动的特性产生重要的影响。计算机运算速度的快速提高,使直接跟踪离散颗粒场中每一个颗粒的数值模拟已成为可能[1,2]。分别用欧拉方法处理气场和用拉格朗日方法处理离散颗粒场,在极少的人为假设下,首次采用三维湍流气相场加三维离散颗粒场对稠密气固两相流进行直接数值模拟,发挥欧拉方法和拉格朗日方法的长处,得到符合实际的模拟结果。

1　颗粒相数学模型

气固两相流中颗粒主要受到下述力的作用: (1)颗粒与颗粒相互接触所产生的力; (2)颗粒与器壁接触所产生的力; (3)气流与颗粒相对运动对颗粒产生的力; (4)重力。以上是颗粒所受到的主要作用力。

根据基本物理定律,两个球形颗粒的对心碰撞过程为: 首先在接触点处发生弹性变形,颗粒在前进方向受到阻力,该阻力的大小与法向变形位移 δ_n 和材料的刚度 k 成正比,在达到最大变形位移时,颗粒停止运动,随后在该力的作用下,沿原来运动直线反弹。对于非完全弹性碰撞,碰撞后颗粒的动能发生损失,动能损失的大小与颗粒材料的物性和碰撞时的相对速度有关,该部分损失在物理上可以归结为在碰撞过程中受到一个与颗粒运动方向相反的力[3],该力的大小等于两颗粒的相对速度与系数 η 的乘积, η 通常称为阻尼系数。

当两颗粒发生偏心碰撞时,相撞点处的接触力可分解为法向分力和切向分力,分别由法向变形位移 δ_n 和切向变形位移 δ 以及法向动能损失和切向动能损失分别进行计算,法向分力的作用结果如同对心碰撞,切向分力的作用结果是对颗粒球心产生一个矩,该矩将使颗粒发生旋转,由该矩和颗粒的转动惯量可求出所产生的角加速度。切向力的极值受到颗粒表面摩擦系数与法向力乘积的限制,当所计算出的切向分力大于该乘积时,两颗粒在接触表面将发生滑动。

对于更一般的情况是两个旋转颗粒发生偏心碰撞,这时除计算法向位移和切向位移外,还应计及由于颗粒自转在接触点处所造成的切向速度。

当一个颗粒同时与几个颗粒相碰撞时,通过矢量叠加可算出该颗粒所受到的合力与合力矩。

颗粒与器壁的碰撞类同于颗粒与颗粒的碰撞,只需用器壁取代另一颗粒。

上述物理过程可通过以下数学模型描述:

$$\vec{f}_{Cnij} = (-k_n \vec{\delta}_{nij} - \eta_n \vec{v}_{rij} \cdot \vec{n}_{ij})\vec{n}_{ij} \tag{1}$$

$$\vec{f}_{Ctij} = -ki\,\vec{\delta}_{ij} - \eta_t \vec{v}_{sij} \tag{2}$$

$$\vec{v}_{sij} = \vec{v}_{rij} - (\vec{v}_{rij} \cdot \vec{n})\vec{n} + r(\vec{\omega}_i + \vec{\omega}_j) \times \vec{n} \tag{3}$$

式中 f_c: 接触力, k: 颗粒的刚度, δ: 颗粒相撞所产生的弹性变形, η: 阻尼系数, v_r: 相对速度, n: 单位法向向量, v_s: 接触点滑移速度, r: 颗粒半径, ω: 颗粒角速度。下标 n 和 t 分别为法向和切向, i, j 为颗粒。

$$|\vec{f}_{Ctij}| \leqslant \mu_f |\vec{f}_{Cnij}| \tag{4}$$

$$\vec{f}_{Ctij} = -\mu_f |\vec{f}_{Cnij}| \vec{t}_{ij} \tag{5}$$

$$\vec{t}_{ij} = \vec{v}_{sij} / |\vec{v}_{sij}| \tag{6}$$

式中 μ_f: 摩擦系数, t: 单位切向向量。

$$\vec{F} = \vec{f}_C + \vec{f}_F \tag{7}$$

$$\vec{v} = \vec{F}/m + \vec{g} \tag{8}$$

$$\vec{\omega} = \vec{T}/I \tag{9}$$

式中 F: 合力, f_F: 流体力, m: 颗粒质量, g: 重力加速度, T: 合矩, I: 颗粒转动惯量。

$$\vec{v} = \vec{v}_0 + \dot{\vec{v}}\,\Delta t \tag{10}$$

$$\vec{r} = \vec{r}_0 + \vec{v}\,\Delta t \tag{11}$$

$$\vec{\omega} = \vec{\omega}_0 + \dot{\vec{\omega}}\,\Delta t \tag{12}$$

式中 v: 颗粒速度向量, Δt: 时间步长, r: 颗粒重心的位置向量。下标 o: 前一 Δt 旧值。

收稿日期: 1999－04－06; 修订日期: 1999－06－22

基金项目: 东南大学科研基金资助项目(9250051024)

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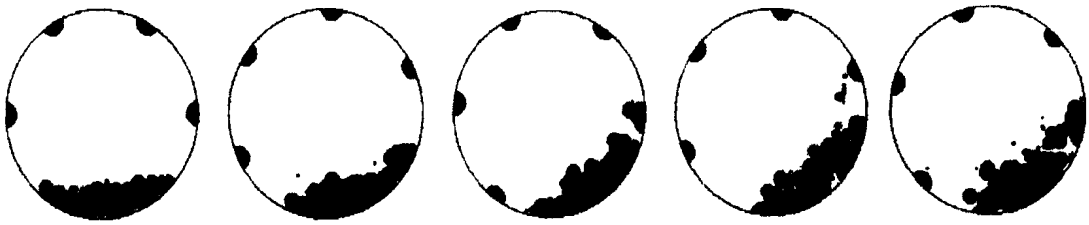


图 1 球磨机中颗粒运动过程

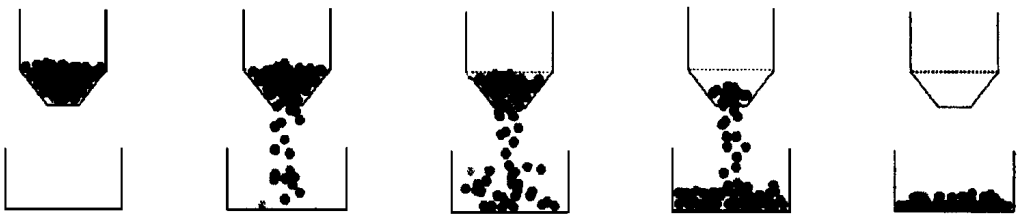
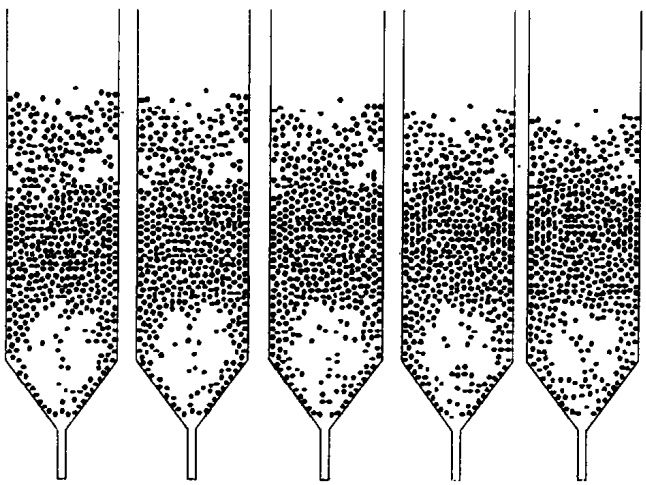


图 2 颗粒由漏斗下落过程



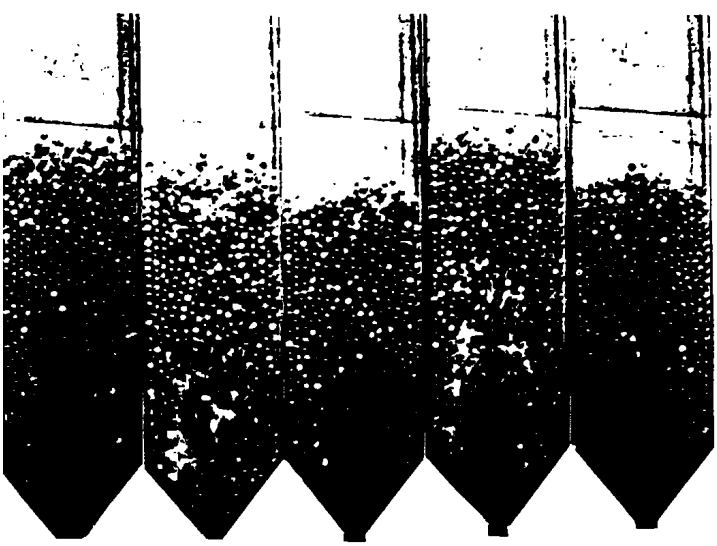


图 3 实验结果与模拟结果的对比

2 气相数学模型

气相场数学模型部分为经典的欧拉方法[4]。在气固两相流中，固相的存在对气体的流动产生影响，该部分影响主要通过空隙率反映出来，由于直接模拟跟踪到了颗粒场中的每一个颗粒，因此通过统计各网格中的颗粒数，即可准确地求出各个网格的空隙率 ε。

3 用直接模拟法所得到的模拟结果

在流化床和气力输送中，流体力对颗粒的运动起着重要的作用，但也有流体力可以被忽略的场合，如球磨机中的颗粒运动和颗粒由漏斗下落的过程。图 1 为在忽略流体力的情况下，颗粒在内壁带有半圆形护甲的筒式球磨机中运动过程的模拟结果，图 2 是模拟得到的颗粒由一漏斗落入位于下方容器的过程。

图 3 是喷动流化床的模拟结果和在一个与模拟条件完全相同的实验装置上所得到的实验摄影的比较，实验装置用透明的有机玻璃制成，实验物料为直径 $d_p = 9$ mm，密度 $\rho = 1042$ kg/m^2 的聚苯乙烯树脂颗粒，颗粒个数为 800，在微机上用了近 2 小时的计算时间。从模拟结果和实验结果的对比可以发现，两者的流化状态取得了非常好的一致性。

4 结束语

由于直接模拟法在模拟中极少采用人为假设，模拟中精确地考虑到每个颗粒的直径、密度、材料刚度、材料摩擦性的影响，因此所得到的模拟结果非常符合实际。同其它气固流动模拟方法相比，该方法的计算量大，目前在微机上所模拟颗粒场的颗粒数目受到限制。随着计算机硬件技术的快速发展，该方法有巨大的发展潜力。

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（渠 源 编辑）

ing method for the system can reduce the influence of quantization error of A/D converter, thereby increasing the measurement accuracy of the temperature-rise rate and enhancing the accuracy of thermal stress calculation. In addition, the system on the basis of a measured thermal stress gives an output in the form of 4 - 20 mA to other systems for analysis, accumulating relevant data for computing turbine service life later on. **Key words**: rotor thermal stress, real-time monitoring, difference measuring method, accuracy

稠密气固两相流的直接数值模拟＝**Direct Numerical Simulation of Dense Gas-solid Two-phase Flows** [刊, 中] /Yuan Zhulin (Thermal Energy Research Institute under the Southeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —465 ~ 466

Gas-phase field and discrete particle field are treated respectively by a Eulerian method and a Lagrangian one. During the treatment of a particle field the effect of particle diameter, specific weight, rigidity of material and friction factor, etc on particle movement has been taken into account. A direct simulation method was employed to simulate funnel flow, the particle movement in a ball mill and a stouted bed. Moreover, tests were conducted to verify the simulation results obtained on the stouted bed. **Key words**: gas-solid two-phase flow, direct numerical simulation

换热系统变工况分析＝**Off-design Performance Analysis of a Heat Exchange System** [刊, 中] /Bao Demei, Fan Deshan, Xu Zhigao (Southeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —467 ~ 470

A new method for analyzing a heat exchange system performance variation is proposed along with the establishment of a relevant linear mathematical model. The proposed method can not only analyze the performance of the heat exchange system as a whole during a change in operating conditions, but also reflect the thermal excursion and temperature changes of each heat exchanger within the system and also the efficiency of the heat exchanger itself. Finally, by taking the boiler heating surface soot-blowing as an example the results obtained from the model and those from a simulated model are compared. It is shown that the proposed method features both simplicity and real-time properties. **Key words**: heat exchange system, off-design operating conditions, thermal efficiency, heat transfer unit, soot-blowing

基于模糊神经网络的高加系统内部故障诊断方法＝**A Method for the Diagnosis of Internal Malfunctions of a High-pressure Heater System Based on a Fuzzy Neural Network** [刊, 中] /Qin Zaicong, Xu Zhigao (Southeastern University), Lu Songlin (Jiangsu Provincial Electrical Power Test Research Institute) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —471 ~ 472

The authors expound the application of a fuzzy neural network for the diagnosis of internal malfunctions in a high-pressure heater system. Practice has shown that the diagnosis model under discussion has broad prospects for engineering applications. **Key words**: failure diagnosis, fuzzy neural network, high-pressure heater system

双列调节级的变工况热力计算方法及应用＝**A Method of Thermodynamic Calculation for Off-design Conditions of a Turbine Dual-row Governing Stage and Its Application** [刊, 中] /Fu Lin, Jiang Yi (Qinghua University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —473 ~ 476

The authors have come up with a thermodynamic calculation method for a turbine dual-row governing stage. Under this method the thermodynamic properties of the governing stage, including post-stage steam enthalpy, can be speedily identified when made known are only such parameters as the relevant geometric characteristics of the stage. The method can be employed for the simplified thermodynamic calculation of heat supply units. **Key words**: dual-row governing stage, algorithm, steam extraction unit

矩阵法和偏微分理论在机组热经济性分析中的应用＝**The Use of Matrix Method and Partial Differential Theory for the Analysis of a Reheat Unit Economic Performance** [刊, 中] /Zheng Xiuping, Zheng Luying, Cai Tianyou (Northeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —477 ~ 480

A general analysis is performed of a power plant reheat-regeneration thermodynamic system with the use of a matrix method and partial differential theory. Given are the calculation results of thermo-economic analytical parameters H_j^o and η_j^o. The proposed method is applicable for both reheat units and non-reheat ones. **Key words**: thermal system, matrix method, partial differential theory, economic performance analysis

弹性转子磁气轴承系统的 H_∞ 控制＝**H_∞ Control of the Magnetic Bearing System of a Flexible Rotor** [刊,