

气固两相流 $k\text{-}\epsilon$ $k_p\text{-}\epsilon_p$ 双流体模型及应用

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【摘要】 以流体 $k\text{-}\epsilon$ 双方程模型为基础, 提出了一种包括颗粒湍动能输运方程和耗散率方程的 $k\text{-}\epsilon$ $k_p\text{-}\epsilon_p$ 两相湍流模型。并对两个垂直上升管道内气固两相湍流进行了数值计算, 计算结果和已有实验结果吻合得很好。

主题词: 两相系统 耦合 湍流 模型

分类号: O359

1 引言

在气固两相湍流的数值模拟中, 为了考虑气体和颗粒之间的双向耦合作用, 过去往往采用以局部追随理论为基础的 Hinze-Tchen 颗粒代数模型^[1]。但是大量的 LDV 实验结果表明, 颗粒的湍流度并非处处比流体湍流度小, 而是时常比流体湍流度大^[2,3]。为此周力行^[4]曾提出了 $k\text{-}\epsilon$ k_p 模型。但在其模型中, 假定颗粒的涡团长度和流体的湍流涡团长度相当。本文作者认为, 颗粒的湍动能的耗散受其自身的耗散方程的制约, 也就是 ϵ_p 方程。并且颗粒的湍流涡团长度 $l_p \propto k_p^{3/2} / \epsilon_p$, $\nu_p \propto k_p^2 / \epsilon_p$ 。这就是本文提出的 $k\text{-}\epsilon$ $k_p\text{-}\epsilon_p$ 两相湍流模型。它全面考虑了粒子湍动能本身的对流、扩散、生成和耗散, 以及与流体之间的相互作用耦合关系。为了验证本文模型的有效性, 对两个垂直上升管道内气固两相湍流进行数值分析, 并和实验结果进行了比较。

2 控制方程、湍流模型及求解方法

假定: (1) 气体和粒子宏观上都是连续介质, 但仅气体在微观上也当作连续介质处理; (2) 粒子相是稀相 (体积分数 $A < 0.01$), 忽略掉粒子项的分压, 认为 $(1-A) \approx 1$; (3) 气体和粒子之间的动量交换是由粘性阻力描述的, 并考虑粒子的重力; (4) 粒子存在层流粘性 μ 并且满足 $\mu/\mu_0 = M/M_0^{5/4}$; (5) 粒子为具有同一直径 d_p 的球体, 大小均匀; (6) 平均流是稳态的不可压缩流。

通过对瞬态控制方程进行 Reynolds 时间平均, 可忽略掉有关体积分数的三阶脉动量。气相各控制方程

$$\frac{\partial (Q U_j)}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial (Q U_i U_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[L \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - Q \overline{U_i U_j} \right] + Q f_i - F_{pi} \quad (2)$$

$$\frac{\partial (Q U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(L + \frac{L_t}{R_k} \right) + \frac{\partial k}{\partial x_j} \right] + G_k - Q E + \frac{1}{S_p} A (-2k + \overline{U_i U_{pi}}) - (U_i - U_{pi}) \overline{A U_i} \quad (3)$$

$$\begin{aligned} \frac{5QU_iE}{5x_j} = & \frac{5}{5x_j} \left(\left(L + \frac{L_i}{R_i} \right) \frac{5E}{5x_j} \right) + \frac{C_1G_kE}{k} - \frac{C_2E^2Q}{k} + \frac{2AQ}{S_p} \left(-E + M \left(\frac{5U_i}{5x_j} \right)^2 \right) \\ & + \frac{2MQ}{S} \left(A' \frac{5U_i}{5x_j} \left(\frac{5U_{pi}}{5x_j} - \frac{5U_i}{5x_j} \right) \right) + \frac{2MQ}{S} \left(\frac{5A}{5x_j} \left(U_{pi}' \frac{5U_{pi}}{5x_j} - U_i' \frac{5U_{pi}}{5x_j} \right) + (U_{pi} - U_i) \frac{5A}{5x_j} \frac{5U_i}{5x_j} \right) \end{aligned} \quad (4)$$

固相各控制方程

$$5(AU_{pi})/5x_j = - (5/5x_j) (\overline{AU_{pi}}) \quad (5)$$

$$\frac{5(AQ_{pi}U_{pi}U_{pi})}{5x_j} = \frac{5}{5x_j} \left(L_2 \left(\frac{5U_{pi}}{5x_j} + \frac{5U_{pi}}{5x_i} \right) - AQ \overline{U_{pi}U_{pi}} \right) + F_{pi} + AQf_i + \frac{5}{5x_j} \left((U_{pi} \overline{AU_{pi}} + U_{pi} \overline{AU_{pi}}) Q \right) \quad (6)$$

$$\begin{aligned} \frac{5}{5x_j} (AQ_{pi}U_{pi}k_p) = & \frac{5}{5x_j} \left(\left(L_2 + \frac{L_p}{R_p} \right) \frac{5k_p}{5x_j} \right) + G_{kp} - AQ_{pi}E_p + \frac{Q_p}{S} A(U_i'U_{pi}' - 2k_p) + (U_i - U_{pi}) \overline{AU_{pi}} \\ & - U_{pi} \frac{5U_{pi}}{5x_j} Q \overline{AU_{pi}} + Qf_i \overline{AU_{pi}} \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{5(AQ_{pi}U_{pi}E_p)}{5x_j} = & \frac{5}{5x_j} \left(\left(L_2 + \frac{L_p}{R_p} \right) \frac{5k_p}{5x_j} \right) + \frac{C_{1p}G_{kp}E_p}{k_p} - \frac{C_{2p}AQ_{pi}E_p^2}{k_p} + \frac{2AQ}{S_p} \left(\left(v_2 \frac{5U_i}{5x_j} \frac{5U_{pi}}{5x_j} - E_p \right) \right) \\ & + \frac{2v_2Q}{S_p} \left(A' \frac{5U_{pi}}{5x_j} \left(\frac{5U_i}{5x_j} - \frac{5U_{pi}}{5x_j} \right) + (U_i - U_{pi}) \frac{5A}{5x_j} \frac{5U_{pi}}{5x_j} \right) + \frac{2v_2Q}{S_p} \left(\left(U_i' \frac{5U_{pi}}{5x_j} - U_{pi}' \frac{5U_{pi}}{5x_j} \right) \frac{5A}{5x_j} \right) \end{aligned} \quad (8)$$

$$F_{pi} = (Q/S_p) A(U_i - U_{pi}) + \overline{AU_i} - \overline{AU_{pi}}, \quad G_{kp} = -Q \overline{U_iU_i} (5U_i/5x_i)$$

$$G_{kp} = AQ \overline{U_{pi}U_{pi}} (5U_{pi}/5x_i), \quad S_p = (Qd_p^2/18L)/(1 + 0.15 Re_p^{0.687}), \quad Re_p = d_p \hat{u} \hat{v} - \hat{v}_p \hat{u} / \nu$$

Q 、 Q_p 为流体和粒子的材料密度, d_p 为粒子直径。在方程(1)~(8)中出现了与颗粒体积分数相关的二阶脉动量 $\overline{AU_i}$ 、 $\overline{AU_{pi}}$ 、 $\overline{AU_{pi}}$, 根据 Hinze 的梯度型扩散假设相关联。雷诺应力项 $-Q \overline{U_iU_i}$ 和 $-AQ \overline{U_{pi}U_{pi}}$ 根据 Boussineq 假定给出。对于二阶相关量 $\overline{U_iU_{pi}}$ 和 $v(5U_i/5x_j)(5U_{pi}/5x_j)$ 采用相关分析法进行模化。在对其它脉动相关量进行模化时, 根据陈景仁的模化法则进行。 $v_t = C_1k^2/E$, $v_p = C_{1p}k_p^2/E_p$ 。方程中各系数分别为: $C_{1p} = C_1 = 1.44$, $C_{2p} = C_2 = 1.92$, $C_{1p} = C_1 = 0.09$, $R_i = 0.7$, $R_p = R = 1.0$, $R_{ip} = R = 1.3$ 。气相在壁面采用无滑移条件, 并采用壁面函数法修正。粒子相采用有滑移条件, 由实验得出的半经验关系式给出 $dU_p/dy = 0.8dU/dy$, $v_p = 0$ 。流道出口按局部单一化处理。以上列出共 10 个方程, 10 个求解变量, 方程组完全封闭, 可以求解。本文采用非交错网格, 应用 SIMPLEC 方法进行求解。求解粒子相连续方程理时用 QUICKER 格式差分。

3 算例及分析

为了验证本文湍流模型的可行性, 本文对吕清刚^[3]和Tsuji^[2]垂直上升直管内气固两相流动进行了数值模拟。文献[3]中实验所用粒子为玻璃球, $d_p = 100\mu\text{m}$, $Q = 2990\text{kg/m}^3$, 文献[2]中所用粒子为聚苯乙烯, $d_p = 200\mu\text{m}$, $Q = 1020\text{kg/m}^3$, 管道直径 $D = 30\text{mm}$ 。

由图 1($d_p = 0.2\text{mm}$, $Re = 23000$) 可看出, 随着粒子载荷比的增加, 气相主流速度分布曲线在主流区愈加平坦, 在壁面附近则变得愈加陡峭。而气流湍流强度随着粒子载荷比的增大而呈减小趋势。由图 2(a) 可发现, 方管内气流速度分布要比圆管内陡峭, 但粒子速度分布却很平坦。由图 2(b) ($d_p = 0.1\text{mm}$, $U_b = 15.96\text{m/s}$, $B = 1.93\%$) 可知, 气流湍流强度分布为中心小, 两壁面最大。颗粒湍流强度分布平坦, 且在大部分区域大于气流的湍流强度。计算结果也得出粒子的湍流强度大于气流湍流强度这一趋势, 并且和实验结果较吻合, 因而本模型在对粒子湍流强度预测上大大优于颗粒代数模型。总的看来, 计算结果和实验结果的吻合程度是令人满意的。

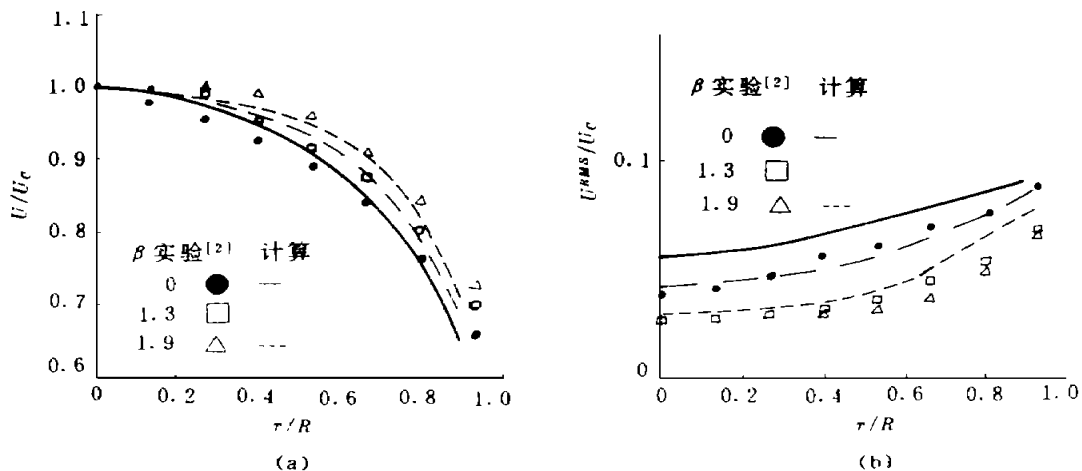


图 1 圆管内不同载荷下气流(a)主流速度分布(b)湍流强度分布

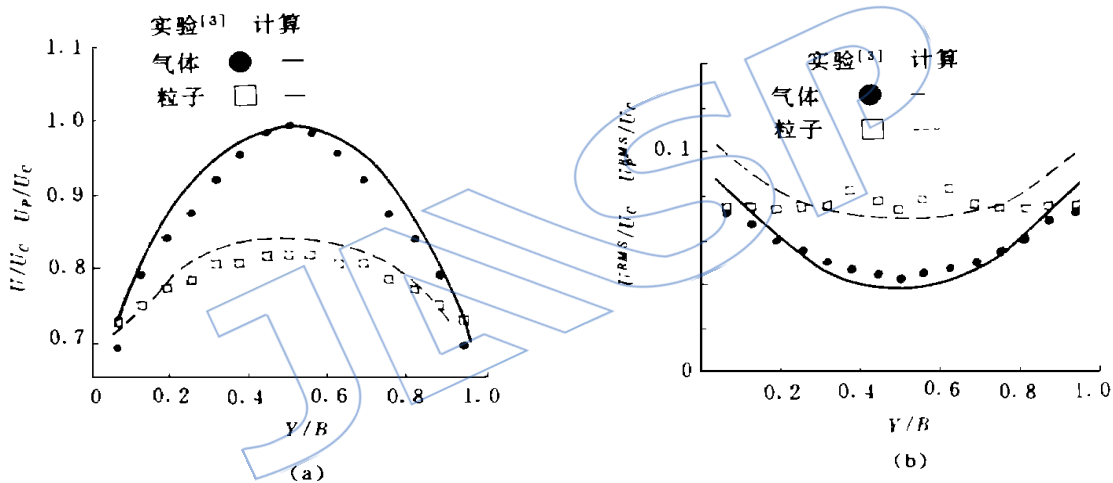


图 2 方管内气流和粒子(a)主流速度分布(b)湍流强度分布

结论 (1)k-Ek_p-E 双流体湍流模型充分考虑了粒子相湍动能产生和耗散的特点, 比只反映粒子湍流跟随理论的代数模型优越。(2)k-Ek_p-E 模型在预测上升直管内两相流动是成功的。计算和实验结果吻合很好。对粒子湍流强度预测, 在定量上还有距离, 有待进一步改进。

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OPTIMIZATION OF MATERIALS YIELD LIMIT FOR RELIABILITY DESIGN

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ABSTRACT

According to aeroengine structure integrity program, fracture critical components must be analysed with damage tolerance concept. Due to crack propagation produced by material defects, working defects or fatigue defects can make structure fracture. Therefore, the sufficient damage tolerance should be maintained. It is realized by selecting material correctly, controlling stress level, using the anti-fracture structures and reliable inspection. In this paper, the structural reliability concept is applied to studying optimization of materials for maximum reliability under certain stress levels and crack sizes, to investigating variation influences of material strength and stress level on structure reliability.

Key words Reliability design Damage Yield limit

OPTIMAL CONTROL OF STRUCTURAL DYNAMIC SYSTEM

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ABSTRACT

A control mathematical model of the dynamic system is established according to the differential equation obtained from the structural dynamic system. Mixed-energy of time-interval is defined and condensation formulas are given with the help of the variational principle. Further the substructural condensation method in structural mechanics is used for the Riccati equation solution, based on the simulation relation between computational structural mechanics and optimal control. Then, the optimal control of the dynamic system is obtained. The numerical example shows the effectiveness of this method.

Key words Dynamic structural analysis Dynamical systems Optimal control

A k - E_k - E_p TURBULENCE MODEL FOR GAS- SOLID TWO- PHASE FLOWS AND ITS APPLICATION

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ABSTRACT

Based on k - E -two-equation turbulence model of gaseous phase, the k - E_k - E_p two-phase turbulence model is presented, which includes the turbulent kinematic energy equation of particulate phase and the dissipation rate equation of that energy. The numerical computations are made for the turbulent gas-solid two-phase flows in two vertical straight channels. The mean velocities and turbulence intensities of gaseous phase and particulate phase, which are predicted with the presented turbulence model, are in good agreement with the experimental results. And it is concluded, that the turbulence intensity of particulate phase is often greater than that of gaseous phase. This conclusion is consistent with available LDV experimental results. Since the algebraic model of particles has no ability to describe the characteristics, the presented turbulence model is very successful in predicting the flow characteristics of turbulent gas-solid two-phase flows.

Key words Two-phase systems Coupling Turbulence model