

电加热管二维温度场计算

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[摘要] 针对水平管、倾斜管中单相流及两相流由于自然对流的影响而使壁温、传热系数沿周向表现出不均匀性,提出了利用外壁面的两个边界条件来克服内壁面边界条件的不足,采用“径向节点内缩”技术的电加热管二维温度场数值计算模型。同时用并联网格电阻发热的概念处理非均匀内热源项。用此模型处理了 $\Phi 32 \times 3$ mm微倾斜管高压汽水两相流传热数据,结果令人满意。

关键词 温度场 源项 两相流 放热系数 边界条件

分类号 TK 124

0 前言

水平管、倾斜管大量存在于电站锅炉及各种工业换热设备中,对于中等偏下热负荷及较高质量流速的情况下,截面上自然对流比强制对流要弱得多,各个参数(壁温、传热系数等)沿周向不均匀性很小。因此,用在垂直管中获得的关联式来预测其传热特性,不会造成较大误差。但对于较高热负荷,即使管内为单相流动,因截面上流体温度梯度较大,这时就不能忽略自然对流的影响。而对于受热管中两相流动,自然对流的存在使得截面上空泡份额分布极不均匀,汽相密度小,存在于管子上部的可能性大,周向不均匀性比单相流体大得多。

近二十年来,发表了许多受热管两相流动正常传热工况及传热恶化工况下的传热系数关联式^[1,2],但这些关联式主要针对垂直管(上升流动及下降流动)小管径($d < 20$ mm)。少量文献研究了水平管中两相流^[3,4],

由于传热系数难以获得,则把着眼点放在研究在给定的运行工况,如压力、质量流速及管径下的临界热负荷,对于给定的汽水系统,显然难于精确预测壁温水平以保证设备的安全运行。

电加热管二维温度场的求解既不属于温度场的正问题,也非反问题(反问题是知道温度场求解边界条件)。

内壁面边界条件即非定壁温,也非定热流(这两项数据就是要求解的量)。若采用传统的方法,如文献[5]中介绍的那样,由于缺乏内壁面边界条件,而使温度代数方程组不能封闭,无法求解。文献[6]提出了电加热管一维温度场计算方法,但只对垂直管适用。电加热管的二维温度场计算方法,还未见文献报道。

事实上,外壁面温度可以通过热电偶测定,而通过外壁的散热量可以通过热效率来确定。如果把测得的外壁温作为外壁面的边界条件,而通过把外壁面的散热量与第二层

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径向节点的温度联系起来,就获得了第二层径向节点温度代数表达式。同理通过把描述极坐标系下带有内热源的偏微分方程在 $P(I, J)$ 控制体内积分,获得 $(I + 1, J)$ 点 $t(I + 1, J)$ 的温度代数表达式。当一直做到与壁面相邻的控制体时,就获得了内壁面分散节点的温度代数表达式,而使所有节点的温度代数方程组封闭,本文将这种方法称为“径向节点内缩法。”同时,对管壁的导热系数及源项作了更细致的处理。流动图样如图 1 所示。

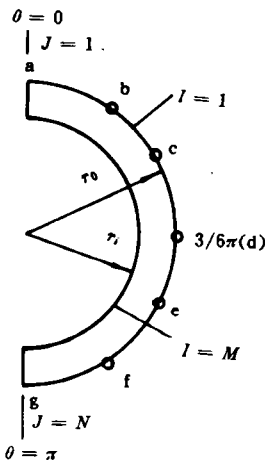


图 2 极坐标系及网格划分

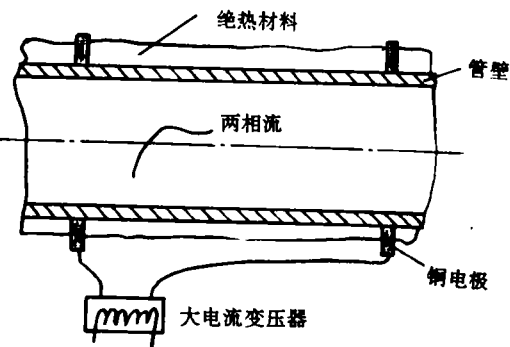


图 1 两相流流动图样

$$\frac{1}{r} \frac{\partial}{\partial r} (rK \frac{\partial t}{\partial r}) + \frac{1}{r} \frac{\partial}{\partial \theta} (\frac{K}{r} \frac{\partial t}{\partial \theta}) + S = 0 \quad (1)$$

式中, K 为导热系数, 是温度的函数, 对于 1G18Ni9Ti 不锈钢, $K = 14.3(1 + 0.01t)$ $W/(m \cdot C)$; S 为体积内热源项, 在电流发热的情况下, 也是温度的函数(以下要作具体分析)。

将式(1)在控制体 P 内积分, 得到

$$a_{p,p} = a_E t_E + a_w t_w + a_N t_N + a_s t_s + b \quad (2)$$

其中: $a_E = \frac{\Delta r}{r_o(\delta\theta)_e/K_e}, a_w = \frac{\Delta r}{r_w(\delta\theta)_w/K_w}$

$$a_N = \frac{r_n \Delta \theta}{(\delta r)_n/K_n}, a_s = \frac{r_s \Delta \theta}{(\delta r)_s/K_s} \quad (3)$$

$$a_p = a_E + a_w + a_N + a_s + a_p^0 - S_p \Delta V \quad (4)$$

因是稳态问题, $a_p^0 = 0$ 。同时, 式中(1)的 $S = S_c + S_p t_p$ 可取 $S_p = 0$ 。式(4)成为:

$$a_p = a_E + a_w + a_N + a_s \quad (5)$$

在式(2)中, $b = S_c \Delta V = S \Delta V = S \cdot [0.5(r_n + r_o) \Delta r \Delta \theta]$ 将式(2)写成节点的形式并重新整理如下

$$\begin{aligned} a_t(I + 1, J) &= a_{pt}(I, J) \\ &- [a_{Et}(I, J + 1) + a_{wt}(I, J - 1) \\ &+ a_{Nt}(I - 1, J) + b] \end{aligned} \quad (6)$$

1 极坐标系统及差分格式

计算二维温度场的极坐标系统如图 2 所示。

考虑到对称性, 取圆管纵向剖面的一半, 将半圆管划分成 $M \times N$ 个节点。同时形成 $(M - 2) \times (N - 2)$ 个主控制容积。外壁面为径向的第一层节点, 内壁面为径向节点的第 M 层节点, $\theta = 0$ 面为周向第一层节点, $\theta = \pi$ 面为周向第 N 层节点。

极坐标系中, 描述有内热源的导热偏微分方程如下:

式(6)就是径向节点内缩法的体现。

$$\bar{Q} = \frac{I^2}{R(I, J)} \quad (15)$$

2 边界条件

外壁面两个边界条件如下:

$$t(1, J) = t_w |_{r=r_0} \quad (7)$$

(由热电偶测得)

$$q_w = q_i(1 - \eta)r_1/r_0 = -K \frac{\partial t}{\partial r} |_{r=r_0} \quad (8)$$

q_i 为视在内壁热负荷, η 为热效率。

根据文献[5], 具有二级截差精度的壁面热流又可写成:

$$q_w = \frac{K}{2\Delta r} [3t(1, J) - 4t(2, J) + t(3, J)] \quad (9)$$

所以:

$$t(2, J) = \frac{1}{4} [3t(1, J) + t(3, J) - \frac{2q_w \Delta r}{K}] \quad (10)$$

$\theta = 0$ 和 $\theta = \pi$ 边界面上为绝热边界条件:

$$\frac{\partial t}{\partial \theta} = 0 |_{\theta=0}, \frac{\partial t}{\partial \theta} = 0 |_{\theta=\pi} \quad (11)$$

写成具体的差分形式为:

$$t(I, 1) = \frac{1}{3} (4t(I, 2) - t(I, 3)) \quad (12)$$

$$t(I, N) = \frac{1}{3} (4t(I, N-1) - t(I, N-2)) \quad (13)$$

式(6)、(7)、(10)、(12)、(13)构成求解二维温度场封闭的代数方程组。

3 源项处理

取轴线方向单位长, 相当于 $M \times N$ 个并联电阻在电压 U 下发热, 总发热量为 $Q = q_i \eta \pi r_1$, Q 写成电阻发热的形式为:

$$Q = I^2 / (\sum_{i=1}^M \sum_{j=1}^N \frac{1}{R(I, J)}) \quad (14)$$

P 控制体的发热量为:

比较式(14):

$$\frac{\bar{Q}}{Q} = \frac{\bar{Q}}{q_i \eta \pi r_1} = (\sum_{i=1}^M \sum_{j=1}^N \frac{1}{R(I, J)})^{-1} / R(I, J) \quad (16)$$

体积内热源

$$S = \frac{\bar{Q}}{\Delta V} = \frac{\bar{Q}}{0.5(r_n + r_s) \Delta r \Delta Q} \quad (17)$$

$R(I, J)$ 为单位长度控制体 P 的电阻, $R(I, J) = \rho(I, J) \times 1/F(I, J)$, $F(I, J)$ 为控制体截面积, $\rho(I, J)$ 为控制体电阻率, 为温度的函数。对于 1Cr18Ni9T, $\rho(I, J) = 7.74 \times 10^{-6} (1 + 7.45 \times 10^{-4} t) \Omega \cdot m$ 。以上是求解温度场的全过程, 具体计算时先假设某个值, 然后采用 TDMA 算法轮流在全场迭代, 直到相邻两次各节点温度相差某一控制小量 ε (ε 可根据计算要求选取) 时, 认为全场收敛。获得全场温度之后, 内壁局部热负荷由下式决定:

$$q_{w1} = \frac{K}{2\Delta r} [3t(N, J) - 4t(M-1, J) + t(M-2, J)] \quad (18)$$

内壁分散点放热系数为:

$$\alpha_{w1} = q_{w1} / (t_{w1} - t_f) \quad (19)$$

t_f 为流体温度, 对于两相流动即为饱和温度 t_s , t_{w1} 其实就为 $t(M, J)$ 。对于超临界流体, t_f 根据压力和焓决定。

4 热效率及流体焓的确定

正式做试验前, 首先进行热效率测定。在试验段中充以单相流体, 控制热负荷, 使外壁温度和正式试验时的壁温水平相近, 测定某一段中进出口温度, 并根据流量获得流体在该段的真实吸热量, 真实吸热量与电加热视在功率的比值, 即为热效率。

试验段某截面的流体焓根据下式热平衡确定:

$$\dot{m}h - \dot{m}C_p t_{in} = Q \pi d \eta \quad (20)$$

进而得到:

$$h = \frac{Q\pi d_i \eta + \dot{m} C_p t_{in}}{m} \quad (21)$$

式中: \dot{m} 为质量流量, t_{in} 为试验段进口单相流体温度。

5 计算结果及分析

按以上模型编制了管壁二维温度场计算程序,处理了 $\phi 32 \times 3$ mm 倾斜管(14° 和 10°) 汽水两相流传热试验数据,获得了各工况下传热系数、周向局部热负荷等。本文发表的数据是 10° 时的数据。

径向分成 9 等分, $\Delta r = 3 \times 10^{-3}/9$ m, 周向分成 7 个节点, $\Delta \theta = \pi/6$, $M = 10$, $N = 7$, 70 个节点, $(10 - 2) \cdot (7 - 2) = 40$ 个主控控制容积。

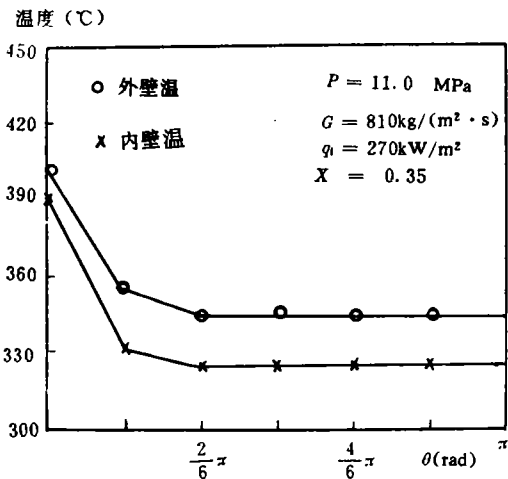


图3 X = 0.35 时内外壁温沿周向变化

本文给出了 $P = 11.0$ MPa, $G = 810$ kg/(m² · s), $q_i = 270$ kW/m² (内壁平均热负荷) 下 $X = 0.35$ 及 $X = 0.488$ 两个工况的计算结果。图 3、图 4 表示的是上顶点壁温刚开

始飞升的情形,上顶点(a点,对照图 1,下同)外壁温已达 400°C ,而其余各点均在 350°C 左右。内壁温与外壁温分布类似,只是内外壁温差开始时较小。由于在 a 点已出现传热恶化, a 点的局部热负荷及换热系数很低, a 点附近管壁发热量不能在 a 点附近释放,势必沿周向扩散,造成 b 点局部热负荷偏高。其余各点放热系数在 38 kW/(m² · °C) 左右波动,在 c 点和 f 点形成两个不大的峰值,因是两相流动,其原因还需进一步研究。

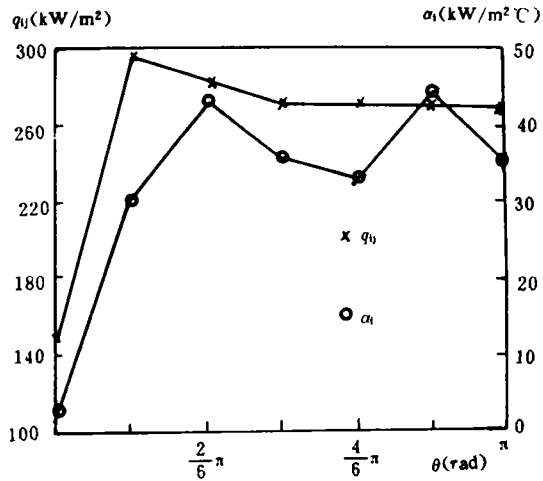


图4 局部内壁热负荷、放热系数沿周向变化

图 5、图 6 表示在较高干度区 ($X = 0.488$) 时,其它工况条件与图 3、图 4 相同时的传热特性。可以看出,除最低点 g 和次低点 f 外,其余各点内外壁温均已飞升,并从上顶点往下近似按线性变化。局部热负荷在上顶点仍然偏低,在其余各点变化不太大。放热系数在 a、b、c、d、e 很低,大约是 f 点的十分之一或更低,这可能是由于主流已是弹状流,除最低点及次低点外,管壁间断地与汽弹接触,而在最低点附近还能维持与液膜接触,传热特性良好。

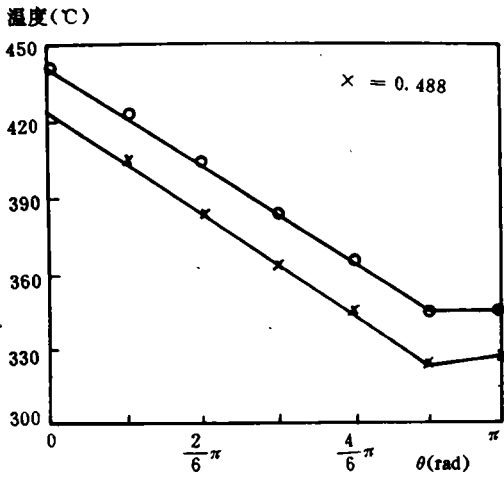


图 5 $X = 0.488$ 时内外壁温沿周向变化

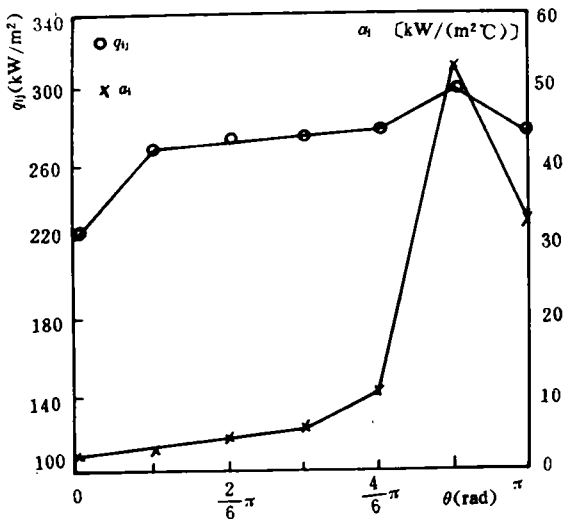


图 6 $X = 0.488$ 时内壁局部热负荷、放热系数沿周向变化

在文献[7]中,给出了小管径垂直管在超临界下的传热系数关联式:

$$\frac{hd}{K_w} = 0.00459 \left(\frac{dG}{\mu_w} \right)^{0.923} \left[\left(\frac{i_w - i_f}{t_w - t_f} \right) \times \frac{\mu_w}{K_w} \right]^{0.623} \left(\frac{V_f}{V_w} \right)^{0.23} \quad (22)$$

本文通过温度场计算,给出了超临界(P 在 23.0 MPa 和 28.0 MPa 之间)下 $\phi 32 \times 3$ mm 的传热系数关联式如下:

$$\frac{hd}{K_w} = 0.00253 \left(\frac{dG}{\mu_w} \right)^{0.965} \left[\left(\frac{i_w - i_f}{t_w - t_f} \right) \times \frac{\mu_w}{K_w} \right]^{0.652} \left(\frac{V_f}{V_w} \right)^{0.702} \quad (23)$$

对比式(22)及式(23),可知式(22)的常数比式(23)的大。这是因为倾斜管顶点的传热系数比相同工况下的垂直管要小。两式的前两个指数相差不大。最后一项 $\frac{V_f}{V_w}$ 是考虑自然对流影响引入的修正,其指数式(23)要比式(22)大许多,说明倾斜管中自然对流的影响较大。

6 结论

本文提出了在无法获得内壁面边界条件的情况下电加热管二维温度场数值计算模型。采用“径向节点内缩”技术,用并联电阻发热的概念来处理非均匀源项。对 $P = 11.0$ MPa 高压汽水两相流传热计算表明,内壁局部热负荷、放热系数随干度增加,不均匀性增大,并做了具体分析。对于超临界流体,给出了倾斜管传热系数关联式。

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verized anthracite coal burner. Such burners feature combustion stability, relatively high combustion efficiency and a desirable tendency of slagging prevention and low NO_x emissions. **Key words:** *pulverized anthracite coal, high concentration, burner*

- (79) **An Experimental Study of Factors Exercising An Influence on the Separation Efficiency of Internal Circulation Fluidized Bed** Wang Yongwu, Wang Huaibin, Chen Chongsu (*Harbin Institute of Technology*)

An experimental investigation was undertaken on a cold-state test model of the factors liable to have an effect on the separation efficiency of internal circulation fluidized bed. On the basis of an analysis of the test results an optimum range of secondary air feeding rate is given with the nozzle angle and layout mode being studied and discussed. **Key words:** *internal circulation, fluidized bed boiler, separation effectiveness, secondary air feeding rate*

- (85) **The Influence of Elevation above Sea Level on the Heat Transfer in Boilers** Che Defu, Hui Shi'en, et al (*Energy & Power Engineering Dept. of Xi'an Jiaotong University*)

Based on the currently available thermal calculation method for boilers analysed and discussed in this paper is the influence of elevation above sea level on the following: boiler furnace heat exchange, convection heat transfer coefficient, radiation heat transfer coefficient, flue gas physical properties and the heat transfer rate of the boiler as a whole. The general tendency of the above influence is also given. **Key words:** *elevation above sea level, heat transfer, boiler*

- (89) **A study on the Structure Optimization of Intensified-Heat-Transfer Elements** Li Weizhong, Mang Gang, Hu Lianxi (*Department of Mechanical Engineering of Fushun Petroleum Institute*)

From the viewpoint of energy comprehensive applications the structure size optimization of intensified-heat-transfer elements has been studied through the use of multi-objective mathematical programming. A suitable optimization method has been developed with the effect of weighted factor on optimization results also being analysed. As a result, the authors provide a major and highly scientific approach for the study, design and utilization of intensified-heat-transfer elements. **Key words:** *intensified-heat-transfer element, optimization, weighted factor, mathematical model*

- (93) **Two-dimensional Temperature Field Calculation of Electric Heating Tubes** Xu Jinliang, Chen Tingkuan (*Xi'an Jiaotong University*)

Taking account of the fact that due to the effect of natural convection the single-phase flow and two-phase flow in horizontal and inclined tubes will lead to a non-uniformity of tube wall heat transfer factor along the peripheral direction the authors have proposed a numerical calculation model for the electric heating tube two-dimensional temperature field by employing the technique of "radial node internal contraction" and solved the problem of inadequacy of inner wall surface boundary conditions by utilizing the two boundaries of the outer wall surface. In addition, the conception of parallel network resistance heat generation has been applied to deal with the non-uniform internal heat source item. With the help of the above-cited model pro

cessed were the heat transfer data of the high-pressure two-phase steam/water flow in $\Phi 32 \times 3$ mm slightly inclined tubes and satisfactory results have been obtained. **Key words:** *temperature field, source item, two-phase flow, heat release factor, boundary conditions, model*

- (98) **Numerical Simulation of Water Film Flow on a Rotating Plate** Li Xuelai (*Harbin Marine Boiler & Turbine Research Institute*)

A numerical simulation is conducted of water film flows on a steam flow-swept rotating plate. The speed distribution of such water film flows has been determined along with the water film thickness distribution variation relationship. **Key words:** *rotating plate, water film, steam turbine, wetness removal*

- (104) **An Investigation of Built-up Laminated Sheet Characteristics under the Condition of Transverse Displacements** Wang Xinfeng, Fang Honghui (*Nanjing Aeronautical Institute*)

By the use of Hellinger-Reissner variation functional the authors present a hybrid single-element model of multi-layer thin sheets and have made an analytical computation of the characteristics of built-up laminated sheets based on the use of hybrid single elements in the presence of transverse displacements. The correctness of the computation method has been corroborated by experiments. **Key words:** *built-up laminated sheet, hybrid single element, stress, calculation*

- (111) **An Exploratory Investigation of the Computer-Based Control of Utility Coal-Fired Boiler Furnace Combustion** Zhou Huaichun, Han Caiyuan (*Key National Laboratory for Coal Combustion Research at Central China Polytechnical University*)

In this paper is discussed the problem concerning the coal-firing system computer-based control for utility coal-fired boilers through the use of conventional control techniques. The authors focus on the following aspects: simulation research approaches, proper PID parameter setting method, the compensation of measurable internal perturbation by the fuel control loop, the treatment of nonlinear fan regulation valve in the air flow rate control loop. Some new understanding as regards a new type of combustion control mode is also presented. **Key words:** *boiler, combustion control, computer applications*

- (117) **Rapid Determination of Coal's Proximate Analysis with the Help of a Thermogravimetric Method** Zhu Qunyi, Zhao Guangbo, Huang Yimin, Chen Chongsu, Yu Hongbin (*Harbin Institute of Technology*)

The authors explore the possibility of determining coal's proximate analysis with the aid of thermogravimetric method and present the test conditions and results. It is found that the results of proximate analysis based on the TG method are in good agreement with those obtained with a standard method. **Key words:** *thermal balance, thermogravimetric method, coal's proximate analysis*

- (121) **The Finite-Time Thermodynamic Performance of Heat Pump Plants with the Heat Leak Effect being Taken into Account** Chen Lingen, Sun Fengrui, Chen Wenzhen (*Wuhan Naval Academy of Engineering*)