低肋横槽管单管外降膜吸收的传热传质模型及计算

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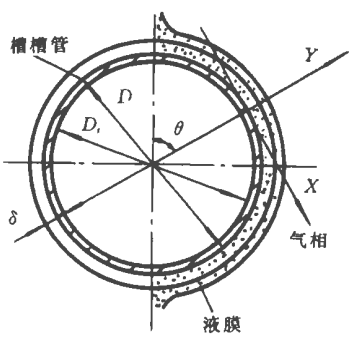
[摘要] 文中提出了一种新的计算低肋横槽管外单管降膜吸收时的数学模型: 把肋片形状为等边三角形、肋片高度小于 0.5 mm的横槽管管外液膜看成是由内层和外层组成。通过理论分析,得出了内层液膜内的速度、温度和浓度分布的解析解,外层则用数值计算的方法求解,内层和外层之间采用二阶耦合法,使内、外层之间能光滑过渡。应用上述数学模型,研究了这种传热管管外液膜内的速度、温度和浓度分布。

关键词　低肋横槽管　降膜吸收　传热传质　数学模型
中图分类法　TK124

1　基本模型

以溴化锂 —— 水吸收器中使用的肋片高度一般小于 0.5 mm 形状为等边三角形的低肋横槽管为对象进行研究。由于肋片高度较小,在喷淋密度 Γ较小时,液膜即可完全淹没肋片,因此,不失一般性。可把在这种传热管外部流动的溶液看成是由两部分组成的: 一部分在肋片之间的流道内流动;另一部分在肋片的外部形成液膜。这样就可把三角形流道之内的区域定义为内层,把三角形流道之外的区域定义为外层。因流速较小,内层中的传热、传质和流动可用理论分析的方法求解; 外层中传热传质和流动情况和光管外液膜的情况类似,可用与文献〔1〕类似的方法求解; 在两个区域的交界面上,用二阶耦合法 (即参数值相等、一阶导数值相等) 使其速度、温度和浓度分布保持连续且光滑过渡。



2　外层的计算模型

坐标系统如图 1所示,取外管壁的圆周方向 (流动方向) 为 x 方向,管外表面的法线方向为 y 方向,传热管的轴线方向为 z 方向,参照文献〔1〕中建立数学模型的方法,对传热管外层液膜可以建立如下的数学模型:

连续方程: $$\frac{\partial(\mathrm{d}u)}{\partial x}+\frac{\partial(\mathrm{d}v)}{\partial y}=0 \tag{1}$$

动量方程: $$\mathrm{d}u\frac{\partial u}{\partial x}+\mathrm{d}v\frac{\partial u}{\partial y}=\frac{\partial}{\partial y}\left(-\frac{\partial u}{\partial y}\right)+\mathrm{d}g\sin\frac{x}{R} \tag{2}$$

能量方程: $$\mathrm{d}c_p u\frac{\partial T}{\partial x}+\mathrm{d}c_p v\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y}) \tag{3}$$

质量方程: $$u\frac{\partial a}{\partial x}+v\frac{\partial a}{\partial y}=\frac{\partial}{\partial y}(D_m\frac{\partial a}{\partial y}) \tag{4}$$

边界条件:

$x=0$时: $$u=\overline{2gs};\ v=0;\ T=T_{in};\ a=a_{in}; \tag{5}$$

$y=H$时: $$u=u_0;\ v=0;\ \frac{\partial u}{\partial y}=\frac{\partial u}{\partial y}|_{y=H};$$
$$\frac{\partial a}{\partial y}=\frac{\partial a}{\partial y}|_{y=H};\ \frac{\partial T}{\partial y}=\frac{\partial T}{\partial y}|_{y=H} \tag{6}$$

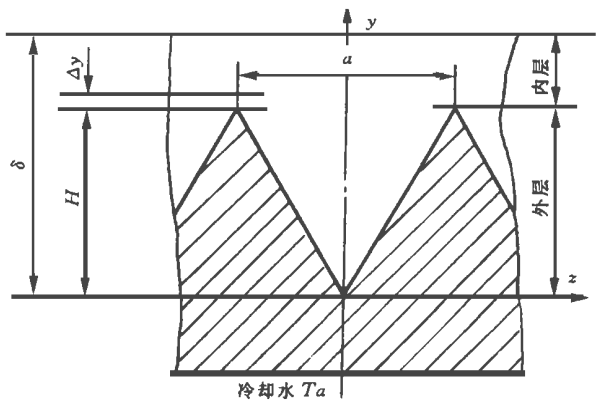


图 1　横槽管的计算模型及坐标选取

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$y = W$时: $\frac{\partial u}{\partial y} = 0$;

$f(T_e, a_e, p_a) = 0$; $\lambda \frac{\partial T}{\partial y} = -\Delta h \frac{dD_m}{a} \frac{\partial a}{\partial y}$ (7)

其中, u、v分别为液膜内溶液的周向和径向速度, T、a分别为溶液的温度和浓度, R为传热管肋片顶部半径, λ、ρ和c_p分别为溶液的导热系数、密度、动力粘度和定压比热, s为喷嘴至传热管顶部的距离, T_{in}、a_{in}分别为喷淋溶液的温度和浓度, $\frac{\partial a}{\partial y}|_{y=H}$、$\frac{\partial a}{\partial y}|_{y=H}$和$\frac{\partial T}{\partial y}|_{y=H}$分别为内外层交界处内层溶液的浓度梯度和温度梯度, W为液膜厚度, H为等边三角形的高, T_e、a_e分别为溶液的饱和温度及饱和浓度, P_a为吸收器中的绝对压力, D_m为溶液的扩散系数, Δh为吸收热。

3 内层的计算模型

选取一个等边三角形流道作为研究对象, 设等边三角形的边长为 a, 则肋片高度 H为$\frac{\sqrt{3}a}{2}$。因流动速度较小, 惯性项和粘性项相比可忽略不计, 在任一 x 处, 流道内的流动、传热和传质方程可简化如下:

$$\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = -\frac{\rho g \sin(x/R)}{\mu} \quad (8)$$

$$\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (9)$$

$$\frac{\partial^2 a}{\partial y^2} + \frac{\partial^2 a}{\partial z^2} = 0 \quad (10)$$

边界条件为: $y = \sqrt{3}z$时, $u = 0$; $a = a_{in}$ (11)

$y = \frac{\sqrt{3}a}{2}$时, $\bar{u} = u_1$; $\frac{\partial \bar{u}}{\partial y} = \frac{u_2 - u_1}{\Delta y}$; $\bar{T} = T_1$;

$\frac{\partial \bar{T}}{\partial y} = \frac{T_2 - T_1}{\Delta y}$; $\bar{a} = a_1$; $\frac{\partial \bar{a}}{\partial y} = \frac{a_2 - a_1}{\Delta y}$ (12)

另外, 根据三角形流道内的热平衡可得:

$$\lambda_s \frac{\partial T}{\partial y}|_{y=\frac{\sqrt{3}a}{2}} = 2\pi \frac{T_b - T_h}{r} \quad (13)$$

其中, u_1, u_2, T_1, T_2, a_1, a_2分别为外层流体在第一、第二节点处的速度、温度和浓度, Δy为 y方向上的网格划分宽度, $\bar{u}$、$\bar{T}$和 $\bar{a}$为三角形流道内任意 y 处 u、T和 a的平均值, T_b和 T_h分别为流道内的平均温度和管内冷却水温度, λ_s为溶液的导热系数, r为三角形流道内的溶液与管内冷却水之间的传热热阻。

参照粘性流体在等边三角形流道中流动时的解析解结果[2], 可设式(8)、(9)、(10)分别具有如下形式的解:

$$u = A(y - B)(3z^2 - y^2) \quad (14)$$

$$T = C + Dy(y^2 - 3z^2) \quad (15)$$

$$a = E - Fy(3z^2 - y^2) \quad (16)$$

$A \sim F$为待定系数, 可由边界条件求出。根据:

$$\bar{u} = \frac{\sqrt{3}}{y}\int_0^{\frac{y}{\sqrt{3}}} u\,dz = \frac{2}{3}A(By^2 - y^3) \quad (17)$$

$$\bar{T} = \frac{\sqrt{3}}{y}\int_0^{\frac{y}{\sqrt{3}}} T\,dz = C + \frac{2}{3}Dy^3 \quad (18)$$

$$\bar{a} = \frac{\sqrt{3}}{y}\int_0^{\frac{y}{\sqrt{3}}} a\,dz = E + \frac{2}{3}Fy^3 \quad (19)$$

及边界条件(11)、(12)可解出:

$$u = [\frac{2}{3a^2}(\frac{u_1 - u_2}{\Delta y} + \frac{T\rho g \sin(x/R)}{2\sqrt{3}\mu})y - \frac{\rho g \sin(x/R)}{4\mu}](3z^2 - y^2) \quad (20)$$

$$T = T_1 - \frac{T_2 - T_1}{3\Delta y}(\frac{\sqrt{3}a}{2} + \frac{6yz^2}{a^2} - \frac{2y^3}{a^2}) \quad (21)$$

$$a = a_{in} - \frac{2}{3a^2}\frac{a_2 - a_1}{\Delta y}(3yz^2 - y^3) \quad (22)$$

同时还可得出:

$$u_1 = \frac{12au_2 + \sqrt{3}\rho g a^2 \Delta y \sin(x/R)}{24\mu + \sqrt{3}\rho g \Delta y + 12a\rho} \quad (23)$$

$$T_1 = \frac{5r\lambda_s T_2 + \sqrt{3}aT_2 + 10\Delta y T_h}{5r\lambda_s + \sqrt{3}a + 10\Delta y} \quad (24)$$

$$a_1 = \frac{6\Delta y a_{in} + \sqrt{3}a a_2}{6\Delta y + \sqrt{3}a} \quad (25)$$

4 计算方法

外层的计算模型与文献[1]的计算模型类似, 可用数值计算的方法求解。与文献[1]所不同的是, 在求解过程中, 每个网格上溶液的物性参数(粘度、密度、比热、导热系数等)均按文献[3]中的物性方程逐点计算。

计算的关键是如何处理内层和外层交界处的边界条件。在交界处, 先假设一个外层 y方向第二个节点上的速度、温度和浓度值, 用式(23)、式(24)和式(25)分别计算边界面上的速度、温度和浓度值, 作为外层计算时的边界条件, 求外层的数值解, 在求解的过程中, 每求解一次, 就把数值解的 y方向第二个节点上的结果代入上述方程对边界条件进行修正,

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直到满足精度要求为止。

5　计算结果与讨论

计算中用到的原始数据如下: 传热管内径为 14mm,肋片顶部直径为 16mm,管长 4900mm,喷嘴到传热管顶部的距离为 4 mm, 喷淋密度 Γ = 0.042kg /(m· s),喷淋溶液的浓度为 59.96% ,温度为 42.78℃ (闪蒸后),吸收器绝对压力为 872 Pa,冷却水进口温度为 32℃。肋片高度为 0.2 mm 时,周向第 15个节点处 y 方向上的速度、温度和浓度分布曲线分别见图 2 图 3和图 4 图中,曲线 1 2 分别对应于横槽管和光管。因 y 坐标是从肋片的根

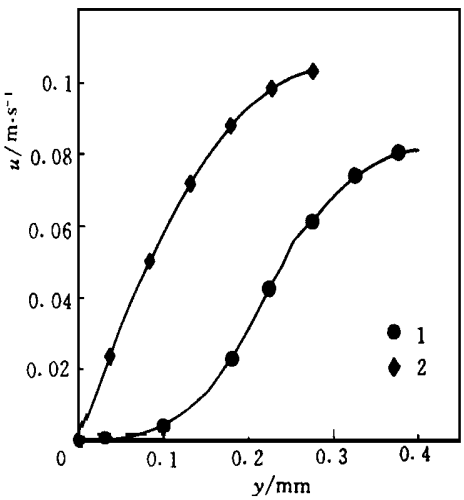

图 2　横槽管外的径向速度分布

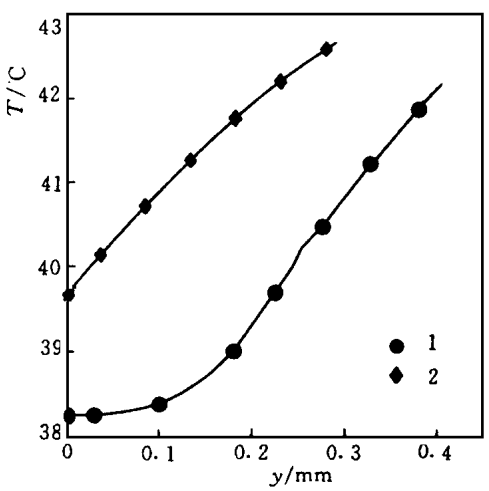

图 3　横槽管外的径向温度分布

部算起的,肋片要排挤一部分流体,故横槽管外的液膜总厚度要比光管的大。y= 0.2 mm处为内层和外

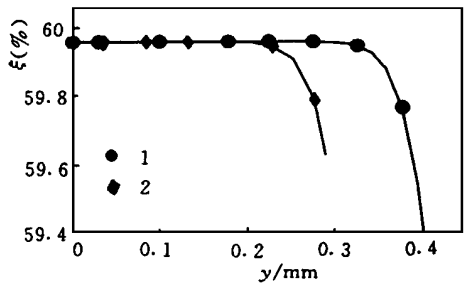

图 4　横槽管外的浓度分布

层的交界点。

横槽管外液膜内的温度 (图 3) 比光管外液膜的温度也有明显降低,这一降低主要表现在肋片根部及内层区域,从浓度分布来看 (图 4),在横槽管外液膜最外层处的浓度比光管外液膜最外层的浓度要低近 0.3个百分点。可见,横槽管对传热传质均有明显的强化作用。吸收量 G和传热量 Q(图 5) 均随肋片高度的增加而增加。与光管 (H= 0时) 相比,肋片高

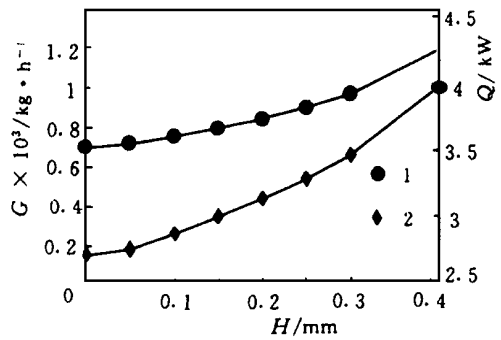

图 5　肋片高度对吸收量和传热量的影响

度为 0.3 mm时,吸收量和传热量的增加幅度均为 30% 左右。

6　结论

(1) 用解析和数值计算相结合的方法求解该类问题是可行的;

(2) 计算结果表明,与光管相比,横槽管内层中的温度值与外层中的浓度值均有明显降低,说明这种传热管对传热传质有明显的强化作用;

(3) 增加肋片高度,可增加强化作用,但肋片高度过大时,文中所给出的方法已不再适用。

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某三元流长叶片振动特性的计算与分析 = **Calculation and Analysis of Three-dimensional Long Blade Vibration Characteristics**[刊, 中]/Gao Chunshan, Li Guiying, Liu Yujie, Zou Jiguo//Journal of Engineering for Thermal Energy & Power. – 1998, 13(5). – 348~ 350

By using a finite element method a calculation and analysis is conducted of three-dimensional long blade vibration characteristics, especially with an in-depth exploratory study of constraint form of the three-dimensional long blade root portion. The relationship between the blade vibration frequency and the root portion constraint form was obtained, thus providing a basis for further analyzing the causes leading to the rupture of three-dimensional flow long blades. **Key words** three-dimensional flow blade, finite element method, vibration

低肋横槽管单管外降膜吸收的传热传质模型及计算 = **Heat and Mass Transfer Model of a Single-tube Falling film Absorption Outside a Low Rib Horizontal Channel Tube and its Calculation** [刊, 中]/Liu Cunfang, (Shandong Industrial University)//Journal of Engineering for Thermal Energy & Power). – 1998, 13(5). – 351~ 353

Presented in this paper is a new mathematical model for calculating the single-tube falling film absorption outside a low rib tube. The liquid outside a horizontal channel tube with a rib assuming the shape of an equilateral triangle and having a height less than 0.5 mm is regarded as consisting of an inner and external layer. Through a theoretical analysis obtained is an analytical solution of the speed, temperature and concentration distribution inside the inner layer liquid film. The external layer is solved by the use of a nume rical calculation method. A second order coupling method is adopted for the liquid between the inner and the external layer so that there will be a smooth transition between the inner and the external layer. The speed, temperature and concentration distribution inside the external tube liquid film of this kind of heat transfer tube has been studied by using the above-mentioned mathematicl model. **Key words** low rib horizontal channel tube, falling film absorption, heat and mass transfer, mathematical model

电站锅炉通用热力计算程序的编制 = **The preparation of a General Thermodynamic Calculation Program for a Utility Boiler**[刊, 中]/Liu Yangfeng, Lu Yukun, Wang Jun(North China Electrical Power Engineering University)//Journal of Engineering for Thermal Energy & Power. – 1998, 13(5). – 354~ 356.

A general thermodynamic calculation program suitable for medium pressure up to super-high pressure coal-fired boilers has been developed by utilizing VB and Fortran language mixed programming. The present paper gives a brief description of the structure of this general program and the approach for solving some key technical problems. The thermodynamic calculation of three boilers of different capacities was also conducted by using the above-cited general program. **Key words** boiler, thermodynamic calculation, program

电厂热力系统工质流量分配计算方法 = **A Study of the Method for Calculating the Working Medium Flow Distribution of a Power Plant Thermodynamic System**[刊, 中]/Yan Shuibao (North China Institute of Water Resources and Hydropower)//Journal of Engineering for Thermal Energy & Power. – 1998, 13(5). – 357~ 359

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