含湿多孔介质内热量迁移的研究*

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〔摘要〕 文中分析了未饱和含湿多孔介质内热湿耦合作用过程的热迁移机理,提出了热量迁移数学模型,讨论了不同边界条件对多孔介质内温度分布的影响状况。

关键词　传热　多孔介质　耦合作用　热湿迁移
分类号　TK124

0　引言

含湿多孔介质作为一种典型的物质体系广泛存在于众多的学科及新兴技术领域之中,对含湿多孔介质传热传质的研究具有重要的理论意义与应用价值。而多孔介质本身结构一般较为复杂,其固体孔隙内往往存在气液两相介质,物质与能量迁移过程同时发生并相互作用。本文将研究热质耦合作用下边界条件对多孔介质内温度变化的影响特性。

1　多孔介质内热湿迁移过程分析

1.1　物理模型

讨论由细小固体颗粒、水和水蒸气组成的多孔介质体系,固体颗粒大小基本相同,平均直径 r 为 0.3 mm,孔隙分布均匀,固体颗粒孔隙率 X为 0.33。由于孔隙细密,可以不计气液两相宏观流动而只考虑其扩散运动。固体骨架不变形,未饱和液态水主要以薄膜水的形式附着在固体颗粒上,液态水与水蒸气充满孔隙空间。

从热量在这种多孔介质结构体系中的传递形式看,一方面,外界热量通过固体颗粒、水和水蒸气以传导的方式传递,增加了整个物质体系的焓;另一方面,水在温度势和浓度势作用下进行扩散,同时吸势发生相变,不断生成水蒸气,水蒸气也在温度势和浓度势驱动下扩散,因而热量在传导的同时也通过水、气扩散过程进行传递。所以,未饱和含湿多孔介质中热扩散与质扩散互为因果而共同形成热质耦合迁移。

假定不存在水的冻结和沸腾,三相间存在局部热平衡,无内热源。同时,为着重分析内部传热过程受外部边界条件变化的影响情况,本文提出如下竖向(z轴自零向下无限延伸)传热模型。

1.2　数学模型

对以上物理条件下的热质耦合迁移过程,应用近平衡态下不可逆热力学线性唯象原理[1],可以建立起未饱和含湿多孔介质内传热微分方程:

$$
\begin{aligned}
&[\rho_s\theta_s c_s+\rho_w\theta_w c_w+\rho_v(X-\theta_w)c_v]\frac{\partial t}{\partial\tau}\\
&=\frac{\partial}{\partial z}\left[(\lambda_e+\rho_w D_{wt}c_w t)\frac{\partial t}{\partial z}\right]+\frac{\partial}{\partial z}\left[(\rho_w D_{ww}c_w t)\frac{\partial\theta_w}{\partial z}\right]\\
&+\frac{\partial}{\partial z}\left[\rho_v D_e(c_v t+H_v)\frac{\partial\rho_v}{\partial z}\right]+\frac{\partial}{\partial z}(\rho_w c_w tK)\\
&-t\frac{\partial[\rho_s\theta_s c_s+\rho_w\theta_w c_w+\rho_v(X-\theta_w)c_v]}{\partial\tau}\\
&-\frac{\partial[\rho_v(X-\theta_w)H_v]}{\partial\tau}
\end{aligned}
\qquad (1)
$$

式中,下标 s、w、v 分别表示固、液、气相,ρ 为密度

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(kg /m^3),θ 为体积百分率 (θ$_w$+ θ$_v$= X), c 为比热 [J/ (kg° K)], t 为温度 (℃), f为时间参量 , Z 为垂直坐标 ,λ$_e$为等效导热系数 (λ$_e$= λ$_s$θ$_s$+ λ$_w$θ$_w$+ λ$_v$θ$_v$, [W /(m° ℃)], D_{ww}和 D_{wt}分别为液态水在多孔介质中的自扩散系数和热扩散系数 [m^2/s, m^2/(s ° ℃)][2], D_e是水蒸气在多孔介质中的等效扩散系数 (m^2/s)[3], K 为水力传导系数 (m /s), H_v 为汽化潜热 (J/kg)。

定解条件为:

$$t_{\tau=0} = t(Z) \tag{2}$$

$$\left[\left(\lambda_e \frac{\partial t}{\partial Z} + \rho_w D_{ww} c_w t \frac{\partial \theta_w}{\partial Z}\right) + D_e(c_v t + H_v)\frac{\partial \rho_v}{\partial Z} + H_v \rho_w D_{ww}\frac{\partial \theta_w}{\partial Z} + \rho_w c_w t K\right]_{Z=0} = T(t_f - t_w) + q_{rad} \tag{3}$$

式中 , T为对流换热系数 [W /(m^2° ℃)], t_f 为外界空气温度 , t_w 为上边界温度 , q_{rad}为边界辐射热流密度 (W /m^2)。

将方程 (1)与水分及水蒸气运动微分方程[4]联立求解 ,可以得到在不同边界条件作用下多孔介质内温度分布。

2　算例与结论

为便于比较复杂边界条件中各个独立因素对传热过程的影响 ,设算例的基本条件如下:

多孔介质初始温度 t_i为 10℃ ,初始含水率 θ$_i$为 0. 10,外界大气压力为 1个标准大气压 ,辐射热流 q_{rad}为 0,外界空气流速 V_f为 1. 0 m /s,温度 t_f为 30 ℃ ,相对湿度 h$_f$为 60% ,当研究某变量的影响时 ,其它变量保持不变。

由计算可知 ,多孔介质内热量迁移受外界空气温度影响较强 ,影响深度基本在 0. 20 m 以内。图 1是空气温度 t_f为 50℃ 时 ,不同时间的多孔介质内部温度动态分布。相对于空气温度而言 ,空气流速对多孔介质内热量迁移的影响深度相似而程度较弱。图 2是当外界空气流速 V_f为 5. 0 m /s时 ,不同时间下多孔介质内部温度动态分布。多孔介质内热量迁移受外界热辐射的影响弱于外界空气温度而强于空气流速。

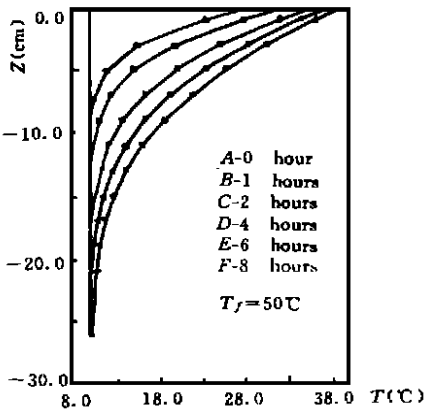

图 1　外界空气温度为 50℃时多孔介质内部温度分布
(曲线自 上而下分别为 A,…… , F)

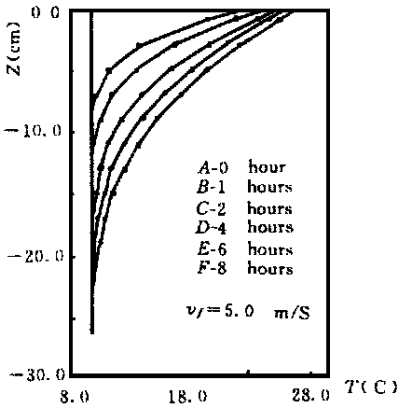

图 2　外界空气流速为 5. 0 m/s时多孔介质内部温度分布
(曲线自 上而下分别为 A,…… , F)

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大型电站锅炉炉内温度场的数值试验研究= **An Experimental Study of the Temperature Field Inside a Large - sized Utility Boiler Furnace by CAT** [刊,中]/Chen Xiaodong, Dong Peng, Cheng Congshu, Qin Yukun (Harbin Institute of Technology)//Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 321~ 323

Through the use of a computer aided test method a fundamental research is conducted of the characteristics of the temperature field in a large-sized utility boiler furnace. On the basis of a three-dimensional numerical simulation of the working medium radiation heat transfer in the furnace obtained is a pertinent in-furnace temperature field distribution law. The numerical test results in most cases are in relatively good agreement with those of the on-site tests. **Key words**: boiler, temperature field, computer aided test

垂直布置倒 U型管内气液两相流稳态特性及脉动特性研究= **A Study of the Steam/Liquid Dual-phase Flow Steady-State and Pulsation Characteristics in a Vertically Placed and Inverted-U Shaped Pipe** [刊,中]/Wu Yining, Lin Zonghu (Xi'an Jiaotong University)//Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 324~ 326

With Freon- 113 serving as a working medium the steady-state and pulsation curves of steam/liquid dual-phase flow in a vertically placed inverted-U shaped tube is studied from both the experimental and theoretical aspects. The test range can be given as follows: outlet pressure P= 0.2- 0.4 MPa, system heating power output Q= 6.4- 10.4 kW, mass flow speed m= 3- 24 kg/m. For the theroetical study adopted is a one-dimensional uniform-phase model with a difference method used for solving a group of conservation equations. Obtained are the steady-state flow ratedifferential pressure characteristics curves. Moreover, a numerical calculation method has been used to simulate pressure-drop type pulsation curves. **Key words**: dual-phase flow, unstability, pulsation

螺旋槽管凝结换热器的研究与应用= **The Study and Application of Condensation Heat Exchangers Consisting of Spirally Corrugated Tubes** [刊,中]/Wu Huiying, Shuai Zhiming (Southeastern University)//Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 327~ 329

An experimental study is made of a condensation heat exchanger with spirally corrugated tubes. Dimensionless correlations are obtained separately for phase transformation-related convective heat transfer in spirally corrugated tubes, tube-outside condensation heat transfer criteria and tube-inside flow resistance. On the basis of the test results the spirally corrugated tubes have been successfully used in power station condensation heat exchangers. **Key words**: spirally corrugated tube, condensation heat exchanger, intensified heat transfer

含温多孔介质内热量迁移的研究= **A Study of Heat Migration in Unsaturated Porous Media** [刊,中]/Jin Feng, Shi Mingheng, Yu Weiping (Southeastern University)//Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 330~ 331

An analysis is given of the mechanism of heat migration under the coupled action of heat and moisture in unsaturated porous media. A mathematical model for calculating the heat migration in porous media is proposed. Also discussed is the effect of different boundary conditions on the temperature distribution in porous media. **Key words**: heat transfer, porous media, coupled action, heat/moisture migration

煤燃烧特征点变化规律的研究= **A study of the Variation Law of Coal-combustion Characteristic Points** [刊,中]/Zhu Qunyi, Zhao Guangbo, et al (Harbin Institute of Technology)//Journal of Engineering of Thermal Energy & Power. - 1997, 12(5). - 332~ 334

An experimental study is performed of the combustion characteristics of thirteen kinds of coals by using a