含不凝气体的蒸汽冷凝换热系数的关联式

熊孟清　林宗虎　(西安交通大学)
刘咸定　(西安建筑科技大学)

〔摘要〕　本文建立了含不凝气体的蒸汽冷凝换热的换热模型，应用该模型和大量换热数据，得到含空气的蒸汽与水平光滑圆管外表面之间冷凝换热系数的关联式，该式应用方便，具有应用价值。

关键词　混合气体　冷凝换热　换热模型　关联式
分类号　TK12

0　引言

含不凝气体的蒸汽(下简称混合气体)冷凝换热系数的关联式很少，仅有的几个关联式可在文献〔1～3〕中找到。由于缺少不凝气体含量恒定条件下的换热数据，关联式多为 Nusselt 凝结换热计算式 T_{Nu} 的修正形式：$T = hT_{Nu}$，式中 h由实验数据确定，一般被看成只是不凝气体含量的函数。文献〔4〕的数值结果表明，h不仅与不凝气体含量有关，且强烈依赖于壁面过冷度。因此，$T = hT_{Nu}$形式的关联式需要更多数据来检验。

Renker[3]应用换热模型 $T = T_{Nu} / (1 + T_{Nu} / T_D)$，给出了迄今最完善的一个关联式，该关联式用于水平圆管外表面上流动混合气体冷凝换热。待定因子 T_D 的经验表达式考虑了不凝气体含量、壁面过冷度和混合气体压力等因素的影响。实际上，T_D 近拟等于混合气体与气—液界面之间的冷凝换热系数。

一般情况下，混合气体冷凝换热取决于气—液界面上的相变换热，即 $T \approx T_D$，因此，以 T_D 为基础建立的换热模型较以 T_{Nu}为基础建立的换热模型更加合理。本文将建立以 T_D 为基础的换热模型，但考虑到文献中不存在 T_D 的表达式，故本文利用文献〔5〕的结果将 T_D 替换为混合气体与不渗透壁面之间的对流换热系数 T_{go}，最后给出主流静止的混合气体在水平光滑圆管外表面上冷凝换热的关联式，该关联式便于工程应用。

1　换热模型

1.1　基本假设

1.1.1　凝结液在过冷壁面上形成连续液膜，并将混合气体与过冷壁面完全隔离。该假设与实际情况吻合，工业冷凝器中凝结方式一般是膜状凝结，即使采取珠状凝结措施，也难维持珠状凝结。

1.1.2　假定混合气体传递给气—液界面的总热量(包括显热和潜热)全部以导热方式通过液膜传递给冷壁面，因液膜非常薄，所以该近似是很合理的。

1.2　换热模型

在假设 1.1.1下，蒸汽侧换热过程可分解成两个并列过程，它们是液膜与过冷壁之间的对流换热和混合气体与气—液界面之间的冷凝换热，后者可

收稿日期　1996-05-06
本文联系人　熊孟清　528251　广东南海南方风机厂

表示成[5]

$$q_i = T_{go} \Delta T_o \quad (1)$$

式中，q_i 是气—液界面上的总热流通量，T_{go}是气—液界面上 Stefan流的速度趋于零 (即凝结率趋于零)时混合气体与界面之间的对流换热系数，ΔF_o是混合气体有效换热温差，其计算公式是[5]

$$\Delta T_o = \frac{Ln^{(1-B_h)}}{B_h}\left(T_g - T_i + B_h \frac{h_{vl}}{Cp_v}\right) \quad (2a)$$

$$B_h = 1 - (1 - B_m)^{\Lambda_o Cp_v / Cp} \quad (2b)$$

$$\Lambda_o = Le^{-2/3} Cp / [C_p + (Y_a - Y_i)(Cp_a - Cp_v)] \quad (2c)$$

$$B_m = (Y_i - Y_a) / Y_i \quad (2d)$$

式中，T_g、T_i和 T_w分别是主流混合气体、气—液界面和过冷壁面的温度，Cp、Cp_a和 Cp_v是主流混合气体、不凝气体和蒸汽的定压质量比热，Y_a和 Y_i是主流混合气体和气—液界面上混合气体中不凝性气体的质量份额，Le是主流混合气体的 Lewis数，h_{vl}是蒸气的气化潜热。

定义蒸汽侧冷凝换热系数 T

$$T = q_w / (T_g - T_w) \quad (3)$$

式中 q_w 是过冷壁面上的热流通量。利用假设 2. 1. 2，有 $q_w = q_i$，结合式 (1)，得到 T的计算公式

$$T = T_{go} \Delta T_o / (T_g - T_w) \quad (4)$$

利用上式计算冷凝换热系数 T时，需要用试算法确定气—液界面温度 T_i，此外还需用蒸汽压方程来计算气—液界面上不凝气体的质量份额 Y_i，这些计算都是很费时间的。为便于工程计算，将式 (4)改写成换热模型，为此做下列处理：(1) 计算 T_{go}时排除液膜的影响，即认为 T_{go}是温度为 T_g 的混合气体与温度为 T_w 的不渗透壁面之间的对流换热系数；(2) 计算 ΔT_o时忽略 $(T_g - T_i)$的影响，并取 $Y_i = 1$，即

$$\Delta T_o = -\Lambda_o \frac{h_{v1}}{Cp_v} Ln^{Y_a} \quad (5a)$$

$$\Lambda_o = \text{Ɫ} Le^{-2/3} \quad (5b)$$

$$\text{Ɫ} = Cp / [Cp + (Y_a - 1)(Cp_a - Cp_v)] \quad (5c)$$

图 1是由式 (2a～2d)计算得到的混合气体有效换热温差，由图可见，式 (5a) 有一定的理论依据。以上处理引起的偏差由待定因子 h予以修正，即将式 (4) 改写成下列换热模型

$$T = -h T_{go} \text{Ɫ} Le^{-2/3} Ln^{Y_a} h_{v1} / [Cp_v (T_g - T_w)] \quad (6)$$

2 换热数据

图 2是实验装置与实验系统的原理图。内外径为∅ 15. 40 mm和∅ 21. 38 mm的光滑圆管水平地安装在钢制圆筒形密闭容器的上部，含空气的蒸汽在圆管外表面冷凝。管外表面温度、主流混合气体温度和冷却水进、出口温度用镍铬—考铜热电偶测量。混合气体真空度用 U型管水银压差计测量，冷却水流量用称重法测量。空气含量是通过测量冷、热两种状态下混合气体的压力和温度而间接测量的，因本文重点是建立换热模型和换热系数关联式，故不详细介绍空气含量的控制与测量方法。表 1列出了换热数据的拟合公式、测量误差和实验范围。实验工况共 398个。

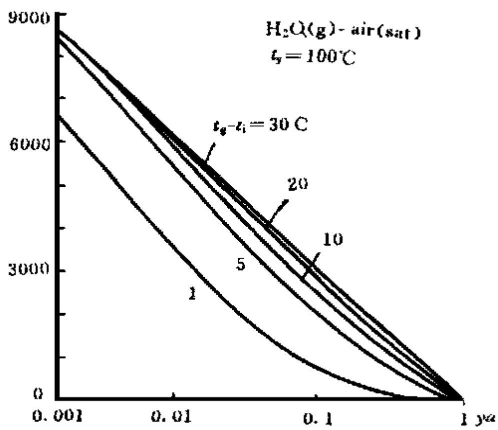

图 1 混合气体有效换热温差

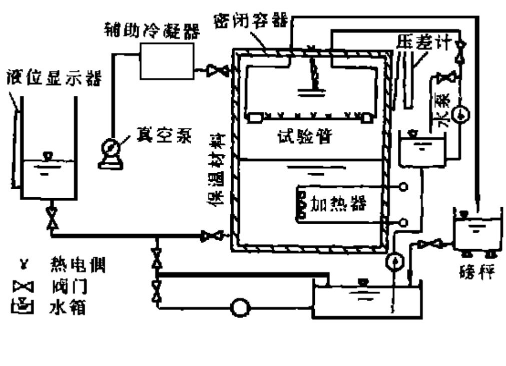

图 2 实验装置及实验系统

表 1 含空气的饱和蒸汽与水光滑圆管外表面之间冷凝换热系数 T的拟合公式

Y_a%	拟合公式	a	b	c	P (kPa)	Δt (℃)	拟合误差%	实验误差%
		10.89	0.64		0.73	2.1~20.1	3.4	≤30.1
		12.89	0.63		1.48	1.7~30.0	7.6	23.5
0.3	$T=a\Delta t^{-b}$	14.26	0.61		2.20	1.4~40.1	11.3	29.0
		16.53	0.63		2.94	2.2~41.4	6.3	20.8
		17.56	0.62		3.67	2.3~49.1	8.4	24.0
		8.87	0.59		0.73	1.6~20.2	7.6	27.9
		11.19	0.61		1.48	1.8~27.4	5.5	24.8
0.5	$T=a\Delta t^{-b}$	11.71	0.56		2.20	1.6~40.0	5.0	28.4
		15.39	0.63		2.94	2.1~43.3	6.2	27.3
		16.69	0.62		3.67	2.6~50.1	7.1	30.7
		7.25	0.59		0.73	1.2~18.7	8.1	30.8
		8.66	0.57		1.48	1.1~30.9	10.3	28.2
1.0	$T=a\Delta t^{-b}$	10.56	0.60		2.20	1.6~34.5	9.5	20.4
		11.72	0.59		2.94	1.5~43.2	12.5	29.6
		12.14	0.58		3.67	1.4~47.1	14.7	28.6
		2.93	0.75		0.73	1.3~16.2	3.8	26.6
		3.47	0.83		1.48	1.7~30.1	4.4	28.7
5.0	$T=a-b\mathrm{Ln}\Delta t$	3.85	0.89		2.20	1.2~36.1	3.2	27.5
		4.21	0.94		2.94	2.0~39.4	5.7	17.6
		4.52	0.98		3.67	1.3~44.8	5.4	25.8
		1.70	0.11	0.0029	0.73	1.1~16.5	5.8	31.2
		2.07	0.11	0.0023	1.48	1.5~28.5	9.6	24.7
10.0	$T=a-b\Delta t+c\Delta t^2$	2.25	0.11	0.0017	2.20	1.6~35.4	13.7	21.7
		2.38	0.099	0.0015	2.94	2.1~40.6	7.1	20.7
		2.51	0.095	0.0013	3.67	1.8~43.9	7.7	22.4

注: P—混合气体压力，kPa；Δt—壁面过冷度，℃；Y_a—空气含量（质量分额）。

3 含空气的饱和蒸汽与水平光滑圆管之间冷凝换热系数的关联式

利用表 1引用的数据可确定模型（6）中的待定因子 h，如图 3所示。图中点是用式（6）计算得到，计算时 T取测量值，T_{go}用以下理论公式计算

$$\frac{T_{go} d_o}{\lambda_f} = 0.563 \frac{(N_\lambda D r / Y)^{1/2}}{\left(\frac{20}{21} Pr + \frac{N}{N_\lambda}\frac{Pr^2}{Y}\right)^{\frac{1}{4}}} Ra^{1/4} \qquad (7)$$

式中，$Ra = |d - d_f| g d_o^3 Pr / d_f \_^2$，$N\_ = d\_ / d_f \_f$，$N_\lambda = d\lambda / d_f \lambda_f$，d λ _是温度为 T_w 的空气的密度、导热系数和动力粘度，d_f、λ_f、$\_f$ 和 Pr 是主流混合气体的密度、导热系数、动力粘度和 Prandtl数。g是重力加速度，d_o是管外径。式（6）中，气化潜热，h_{v1} 按 T_w 计算，Cp、Cp_a 和 Cp_v 取主流混合气体中的值，

图中实线是拟合曲线.

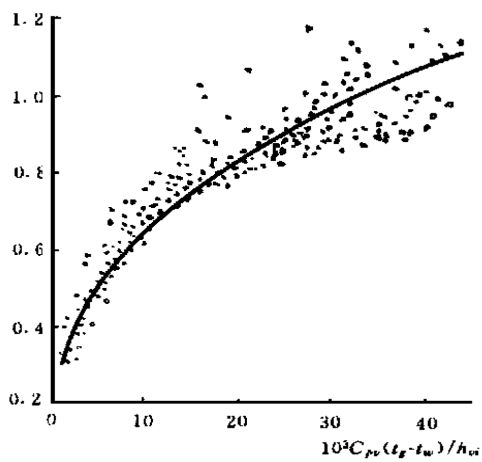

图 3 待定因子 h

$$h = 0.2737\left[10^{3}Cp_{v}\left(T_{g}-T_{w}\right)/h_{v1}\right]^{0.37} \quad (8)$$

其标准误差为 8.8%。若将 h拟合为 $(T_g - T_w)$ 的函数,则标准误差为 11.6%。本文推荐式 (8) 作待定因子 h的经验表达式,于是得到冷凝换热系数的关联式

$$T = -273.7T_{go}YLe^{-2/3}Ln^{Y}{}_{a}\left(\frac{10^{-3}h_{v1}}{Cp_{v}\left(T_{g}-T_{w}\right)}\right)^{0.63} \quad (9)$$

该关联式的适用范围:空气质量分额 $Y_a = 0.3\% - 10.0\%$,混合气体压力 $P = 0.73 - 3.67$ kPa,壁面过冷度 $(T_g - T_w) = 1.1 - 50.1$ K (参考表 1)。

4 结论

(1) 应用换热模型 (6) 得到了标准误差为 8.8% 的蒸汽—空气混合物冷凝换热系数关联式 (9),这说明模型 (6) 具有应用价值。

(2) 式 (9) 在宽广的范围内与实验数据吻合,且应用方便。

参 考 文 献

1 Henderson C L, et al. Film condensation in the presence of a noncodensable gas. J. of Heat Transfer, 1969, 91: 447—450

2 Meisenburg S J, et al. The influences of small concentrations of air in steam on the steam film coefficient of heat transfer. AIChE J., 1935, 31: 622—638

3 Lydersen A L. Fluid flow and heat transfer. John Wiley & Sons, 1979. 247

4 Minkowycz W J, et al. Condensation heat transfer in the presence of noncondensables, interfacial resistance, superheating, variable properties, and diffusion. Int J. Heat Mass Transfer, 1996, 9: 1125—1144

5 熊孟清 等. 含不凝性气体的蒸气冷凝换热计算方法的研究. 西安建筑科技大学学报, 1996, 26(3): 307—310

燃机技术的进展

“Brennstoff-wärme-Kraft” 1996年 4月号报导了 1.0到 600 MW 功率等级的固定式燃气轮机和燃气轮机装置的发展情况,这些燃机中 51% 是以天然气工作的, 28% 是以双燃料工作的,其余是以液体燃料工作的。

预测 2000年后燃机的前景是令人乐观的。指出了最近 10年的技术成就:热效率增加 15% (相对值),比功增加 20% (相对值),燃气温度增加 150 K,压比增加 1倍, NOx 排放量减少 10%,进一步完善了工艺 (冷却、防腐蚀及其它措施)。指出,研制了 200 MW 功率等级的单轴机器,并利用了燃料在燃烧室中顺序 (双级) 燃烧过程 (GT24和 GT26型燃机)。

Siemens KWU、GE、Mitsubishi和 Westinghouse四家公司都在研制蒸燃联合装置,其中利用蒸汽冷却涡轮叶片和燃烧室。

在 50 MW功率级别燃气轮机中,指出罗尔斯—罗伊斯公司和西屋公司的“Trent”发动机,设计压比 35,热效率高达 42.5%。其他公司的许多燃气轮机具有 37%—40% 热效率,索拉公司燃机高压涡轮第一级采用了由陶瓷制成的静子叶片。

通过改进高压压气机的气动特性,循环中采用中间冷却、回热和燃气重新加热可使效率接近 50%。鉴于 A. Kalina提出的过程 (Kalina循环),美国 Exergy公司预期可使动力装置效率再增加 3%。西屋公司致力于远景的 W501D5/F级联加湿先进燃机 (CHAT) 的研究,其效率可与联合循环装置效率相比较。

(思娟 供稿)

scheme some meaningful conclusions were obtained, which can serve as a solid basis for parameter optimization and selection in future design work. **Key words**: gas turbine, simulation technology, mathematical model

太阳能集热器系统的四维热网络动态仿真模型= **Dynamic Simulation Model of a Four-dimensional Heat Network for a Solar Energy Collector System**[刊,中]Chou Qiaoli, Ye Hong, et al (China National University of Science& Thechonology) //Journal of Engineering for Thermal Energy& Power. - 1997, 12(5). - 388~392

The authors have for the first time come up with the conception of a unit(differential) section separate node point heat resistance and heat capacity four-dimensional heat network for a solar energy collector system and on this basis set up a heat collection process dynamic emulation model for the solar energy collector system with a cavity absorber-trough paraboloidal mirror. Under the conditions of a variation of all outside driving forces this model can be used not only to determine the variation of temperature distribution with time of any section of a component but also obtain the spatial distribution of the temperature of each component at any time along the collector system, thereby realizing for the first time the four-dimensional dynamic emulation of the operating conditions of a large-sized solar energy collector. **Key words**: cavity absorber, solar energy collector, Four-dimensional heat network dynamic emulation

机组旁路系统减温减压装置热力特性的计算机分析= **Computer Aided Analysis of the Thermodynamic Properties of a Pressure and Temperature Reduction Device for a Steam Turbine Bypass System**[刊,中]/Zhang Qi, Wang Shizhong, Wang Huaibin(Harbin Institute of Technology) //Journal of Engineering for Thermal Energy& Power.- 1997, 12(5).- 369~373

On the basis of an IFC formula and one-dimensional search method realized are a computer-aided calculation of steam thermodynamic properties and a computer-aided search of steam enthalpy-entropy diagram. Through the use of two-phase flow theory and compressible fluid thermodynamic principles the problem of steam and cooling water mixed flow multi-stage multi-orifice throttling can be transformed into a problem of iterative root extraction of a nonlinear equation. The above makes it possible to perform a computer-aided analysis of the thermodynamic properties of a pressure and temperature reduction device for a steam turbine bypass system. **Key words**: steam turbine, bypass system, pressure and temperature reduction device, thermodynamic properties, computer-aided analysis

汽泡生长诱导的速度场= **An Induced Velocity Field of Steam Bubble Growth**[刊,中]/Gu Pingdao, Lu Changgen(Jiangsu Petrochemical Institute) //Journal fo Engineering for Thermal Energy& Power. - 1997, 12(5). - 374~376

With the help of Apollonius conformal transformation and Fourier series method obtained is an induced velocity field of steam bubble growth process in a stationary flow field. **Key words**: steam bubble expansion, induced velocity field, conformal transformation, expansion circle

含不凝气体的蒸汽冷凝换热系数的关联式= **A Correlation of Condensation Heat Exchange Factor of Steam Containing Non-condensable Gases**[刊,中]/Xiong Mengquing, Lin Zonghu(Xi'an Jiaotong University), Liu Shengding(Xi'an Architectural University of Science& Technology) //Journal of Engineering for Thermal Energy& Power.- 1997, 12(5).- 377~380

The authors have established a heat exchange model for condensation heat exchange of steam-containing non-condensable gases. By using the said model and numerous heat exchange data a correlation for factor of condensation heat exchange between air-containing steam and the outer surface of a horizontal smooth round tube is obtained, which has practical engineering applications and is easy to use. **Key words**: mixed gases, condensation heat exchange, heat exchange model, correlation

开孔金属薄板温度场和导热热阻的测定与计算= **The Determination and Approximate Calculation of Perforated Metal Sheet Temperature Field and Heat Conduction Thermal Resistance**[刊,中]/Yang Zifen, Hong Bo, et al(Shanghai Jiaotong University)//Journal of Engineering for Thermal Energy & Power.－1997,12(5).－381～384

Instead of the rather complicated analytical method and computer-aided numerical method for solving two-dimensional steady-state heat conduction problem of perforated metal sheets this paper proposes an electroconductive paper-based thermoelectrical analogy method. The said method has been used to solve the temperature field and heat conduction thermal resistance of six kinds of typical perforated metal sheets in a simple and speedy manner and also with a relatively high accuracy. The derived approximate calculation formula features rationality, simplicity and a relatively high precision, which contribute to its practical value for making engineering evaluations. **Key words**: metal sheet, steady-state heat conduction, thermoelectrical analogy, approximate calculation

火电厂热力系统热平衡的拓扑算法= **Topology-based Calculation of the Thermodynamic System Heat Balance of a Thermal Power Plant**[刊,中]/Yue Hong(Zhongqing University)//Journal of Engineering for Thermal Energy & Power.－1997,12(5).－385～387

The thermodynamic system heat balance calculation method based on a topological analysis is considered as the most successful computer-based method for calculating thermal power plant heat balance. For the first time this paper makes an in-depth study of this subject, including an overview of the said method, related issues in software design and an analysis of the prospects of its application. It provides a totally new viewpoint in thermodynamic system heat balance calculation. **Key words**: thermodynamic system, topological analysis, heat balance

叶栅风洞试验微机监控系统= **A Computer-based Monitoring System for Turbine Cascade Wind Tunnel Tests**[刊,中]/Liu Wendong, Sun Zhaoqiang, et al(Harbin NO.703 Research Institute)//Journal of Engineering for Thermal Energy & Power.－1997,12(5).－393～394

Key words: turbine cascade wind tunnel test, microcomputer, monitoring system

Edited and Published by Harbin 703 Research Institute and Editorial Staff of this Journal

Printer: Printing House of Harbin Institute of Technology

Address: P.O. Box 77, Harbin, China

Tel: (0451)5650888-2092

Fax: (0451)5662885

Post Code: 150036

Periodical Registration: ISSN 1001-2060 CN23-1176/TK

Distributed by China International Book Trading Corporation

P.O. Box 399, Beijing, China