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管内强化对流换热的热力经济性分析

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[摘要]　鉴于管内换热和阻力同步增长的事实,依据 Webb 指标对管内强化对流换热方式下传热和流阻的综合热力性能进行了推导,得到了热力性能指标 Q/Q_S、P/P_S 和 F/F_S 与管内对流换热努氏数 Nu 和管内阻力系数 λ 之间的函数关系式。在此基础上,对螺旋槽管强化管内换热的热力性能进行了分析。

关键词　强化管内换热　对流换热　热力性能　螺旋槽管
中图分类号　TK124

1　Webb 热力性能指标

实验和理论研究发现 L 管内对流换热的强化往往以阻力的增加为代价。为此有必要对管内强化对流换热方式下传热和流阻的综合性能进行评价。已有的评价方法,以 Webb[1] 提出的热力性能指标最为直观和简单,它们是:

(1)相同换热面积($F/F_S=1$)的泵功($P/P_S=1$)条件下,强化元件与光管的换热量之比(Q/Q_S);

(2)相同换热面积($F/F_S=1$)和换热量($Q/Q_S=1$)条件下,强化元件与光管所耗的泵功之比(P/P_S);

(3)相同泵功($P/P_S=1$)和换热量($Q/Q_S=1$)条件下,强化元件与光管所需的换热面积之比(F/F_S)。

本文将根据上述三个热力性能指标,推导出它们与管内对流换热努氏数 Nu 和管内阻力系数 λ 之间的函数关系式,从而便于对管内强化传热元件的热力性能进行评价和分析。

2　热力性能计算公式的推导

2.1　在推导上述热力性能计算式之前,先作以下假设:

(1)与管内流体对流换热热阻相比,管内流体热阻、管壁金属导热热阻以及管壁污垢热阻忽略不计。对大多数以管内热阻为主导热阻,从而需要对管内进行强化传热的情况来说,这一假设是合理的,于是我们有:

$$Q \approx \alpha F \Delta T_m \tag{1}$$

其中: α 为管内对流换热系数;

F 为换热面积, $F=\pi dL$ (2)

d、L 分别为换热管内径和换热管长度;

ΔT_m 为对数传热温差

(2)换热管内径 d 和传热差 ΔT_m 相同,且流体的物性与换热面形状无关,也认为相同。

(3)比较的基准面为光管,且光管参数一律以下标 S 表示。

2.2　下面将对热力性能 Q/Q_S 的计算式进行推导。

流体流过换热段所需泵功 P 为:

$$P=A\cdot\Delta P\cdot u \tag{3}$$

其中: A 为换热管截面积, $A=\pi d^2/4$ (4)

ΔP 为换热段压降, $\Delta P=\lambda\frac{L}{d}\frac{\rho u^2}{2}$ (5)

将式(4)和式(5)代入式(3)得到泵功计算式为:

$$P=\pi dL\rho/8\cdot\lambda u^3 \tag{6}$$

将式(2)代入式(6)并整理得:

$$\lambda u^3=8P/(F\rho) \tag{7}$$

在相同换热面积和泵功的前提下,根据假设(2)由式(7)可得:

$$(\lambda u^3)_{Re}=(\lambda_S u_S^3)_{Re_S} \tag{8}$$

其中下标 Re、Re_S 分别为相同泵功和换热面积条件下所对应的强化元件管内雷诺数和光管管内雷诺数。

由 $Re=ud/\nu$ 并根据假设(2)有:

$$(Re_S/Re)^3=(u_S^3)_{Re_S}/(u^3)_{Re} \tag{9}$$

根据式(8)和式(9)可得

$$(Re_S/Re)^3=\lambda_{Re}/(\lambda_S)_{Re_S} \tag{10}$$

光管管内阻力系数可根据公式 $\lambda_S=c_1 Re^{-0.25}$ 计算[2],则有:

$$\frac{(\lambda)_{Re}}{(\lambda_S)_{Re}}=\frac{(\lambda)_{Re}}{(\lambda_S)_{Re}}\cdot\frac{(\lambda_S)_{Re}}{(\lambda_S)_{Re_S}}=\left(\frac{\lambda}{\lambda_S}\right)_{Re}\cdot\frac{c_1 Re^{-0.25}}{c_1 Re_S^{-0.25}} \tag{11}$$

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将式(11)代入式(10)并整理得:

$$Re/Re_S=(\lambda/\lambda_s)_{Re}^{-\frac{1}{2.75}} \tag{12}$$

在换热面积相同的前提下, 由假设(1)和假设(2)可得:

$$\frac{(Q)_{Re}}{(Q_S)_{Re_S}}=\frac{(\alpha)_{Re}}{(\alpha_S)Re_S}=\frac{(\frac{\alpha d}{k})}{\frac{\alpha_S d}{k})_{Re_S}}=\frac{(Nu)_{Re}}{(Nu_S)_{Re_S}}$$

$$=\frac{(N_u)_{Re}}{(Nu_s)_{Re}}\cdot\frac{(Nu_S)_Re}{(Nu_S)_{Re_S}} \tag{13}$$

光管管内换热努氏数可根据公式 $Nu_S=c_2 Re^{0.8}$ 计算[3], 则有:

$$(Nu_S)_{Re}/(Nu_S)_{Re_S}=(Re/Re_S)^{0.8} \tag{14}$$

将式(14)代入式(13)得:

$$(Q)_{Re}/(Q_S)_{Re_S}=(Nu/(Nu_S)_{Re}\cdot(Re/Re_S)^{0.8} \tag{15}$$

将式(12)代入式(15)得到相同泵功及换热面积条件下, 强化元件与光管的换热量之比 Q/Qs 的计算式:

$$Q/Q_S=(Nu/Nu_S)_{Re}\cdot(\lambda/\lambda_S)_{Re}^{-0.291} \tag{16}$$

式中$(Nu/Nu_S)_{Re}$和$(\lambda/\lambda_S)_{Re}$分别为相同雷诺数下强化元件管内与光管管内努氏数之比和阻力系数之比。

用相似的方法可以推导出相同泵功和换热量条件下, 强化元件与光管换热面积之比的计算式:

$$F/F_S=(Nu/Nu_S)_{Re}^{-1.41}\cdot(\lambda/\lambda_S)_{Re}^{0.41} \tag{17}$$

可以得到相同换热量和换热面积条件下, 强化元件与光管泵功之比的计算式:

$$P/P_S=(Nu/Nu_S)_{Re}^{-3.438}\cdot(\lambda/\lambda_S)_{Re} \tag{18}$$

由式(16)、式(17)和式(18)可以进一步得到热力性能 Q/Q_S、P/P_S 和 F/F_S 之间的相互关系:

$$Q/Q_S=(P/P_S)^{-0.291}=(F/F_S)^{-0.709} \tag{19}$$

式(19)表明: (1)相同 Re 数据情况下, Q/Q_S 越大, P/P_S 和 F/F_S 也就越小; (2)对同一种管内强化换热元件, 三个热力性能指标只要知道其中之一, 便可求得另外两个的值, 因此通常只需给出 Q/Q_S 的值就可判别强化元件的热力性能。

3　热力性能计算公式的应用

螺旋槽管(图 1 所示)是一种性能优良的强化传热管件, 对管内单相流体的对流换热有着显著的强化作用。文献[4] 为此进行了大量的试验研究, 得到了不同结构参数螺旋槽管的管内阻力和换热试验数据。由于换热和阻力同步增长的原因, 从这些阻力和换热数据中很难直接判别出哪种结构参数的螺旋槽管具有更好的热力性能, 为此我们依据式(16)得到如图 2 所示的螺旋槽管热力性能曲线, 图中螺旋槽管的结构参数见表 1。

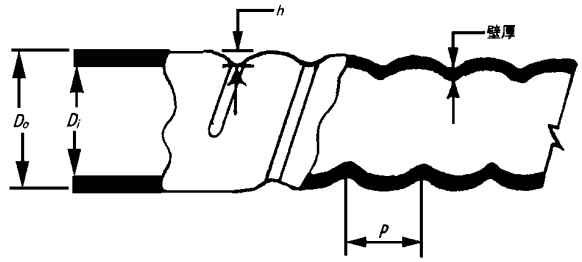

图 1　螺旋槽管结构示意图

表 1　螺旋槽管结构参数(图 2 中)

符号	管号	D_O(mm)	D_i(mm)	h(mm)	p(mm)	h/D_i	p/h
○	1	39.92	36.95	1.22	20.6	0.033 0	16.89
□	2	39.97	37.01	1.60	20.9	0.043 2	13.06
△	3	40.05	37.13	2.00	21.1	0.053 9	10.55
◇	4	40.12	36.97	1.53	16.0	0.041 4	10.45
☆	5	40.22	37.09	1.71	16.1	0.046 1	9.41

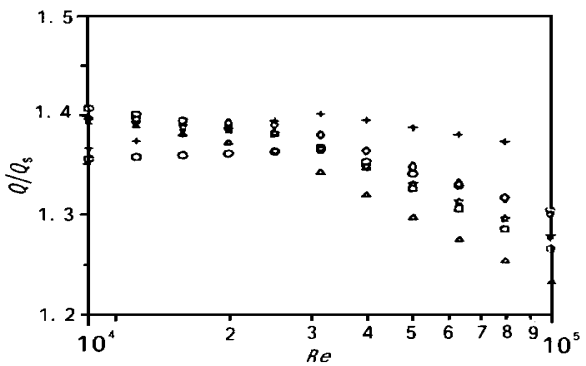

图 2　相同泵功和换热面积条件下, 螺旋槽管与光管的换热量之比

由图 2 可见:

(1)相同泵功和换热面积条件下, 螺旋槽管换热量可较光管提高 23%—41%;

(2)与其它试验管相比, 2 号管、4 号管及 5 号管的性能较高, 在 $Re=10^4-3\times10^4$ 范围内, 它们的换热量可较光管提高 40%左右;

(3)在试验范围内, Q/Q_S 曲线基本上随着 Re 数的增加而减少, 这表明螺旋槽管在低 Re 数时表现出较高的强化传热性能。

上述分析与文献[4] 的结论是一致的。

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Storage System〔刊, 中〕/Fang Guiyin (China National University of Science & Technology)//Journal of Engineering for Thermal Energy & Power. —1999, 14 (2). —92~94

The dynamic characteristics of an ice direct storage system is analyzed with a relevant physical model being set up. With the help of this model obtained is the variation of the ice storage radius and cold storage rate with time. The model forecast values agree relatively well with the measured ones. This model can be used for providing a theoretical basis for the design and optimization of ice direct storage systems. **Key words**: air conditioning cold storage, ice direct storage system, dynamic characteristics

异抗坏血酸稳定亚硫酸盐的制备及其贮存稳定性研究=**Preparation of Isoascorbic Acid Stabilized Sulfite and a Study of Its Storage Stability**〔刊, 中〕/Xiong Rongchun, Wei Gang, Zhang Xiaodong (Beijing Chemical Engineering University)//Journal of Engineering for Thermal Energy & Power. —1999, 14 (2). —95~98

The inhibition of isoascorbic acid on sulfite automatic oxidation was studied by way of oxygen removal and air oxidation tests. The investigation results show that Cu2+ as a radical chain reaction initiator can accelerate the reaction of sulfite with oxygen. The isoascorbic acid as a radical absorbent can inhibit the reaction by removing the free radical produced in the sulfite oxidation process. Water pH value, hardness and alkalinity do not exercise any influence on the reaction. The test results provide an important evidence for the free radical chain mechanism of sulfite oxidation and also an effective method for preventing sulfite failure during its storage. **Key words**: sulfite, isoascorbic acid, free radical chain reaction, initiator, absorbent

富氧膜技术及其装置试验研究=**An Experimental Study of Oxygen—rich Membrane Technology and Related Equipment**〔刊, 中〕/Lin Xiangdong, Chen Xinghai, Huang Fei (Harbin 703 Research Institute)//Journal of Engineering for Thermal Energy & Power. —1999, 14 (1). —99~101

Based on the performance testing of an oxygen—rich membrane device the authors give a comprehensive review concerning the effect of oxygen—rich concentration and oxygen—rich air production rate under various operating regimes on the oxygen—rich membrane device performance and operating conditions (pressure ratio, air supply rate and operating temperature). Discussed are some problems during the practical application of such devices. In addition, an analytical study is conducted of the merit of combustion supporting effect of oxygen—rich air from the combustion technology viewpoint. **Key words**: membrane method of oxygen enrichment, device, performance test, combustion technology

多压凝汽器在 200MW 汽轮机组中的应用=**The Use of a Multi—pressure Condenser in a 200 MW Steam Turbine Unit**〔刊, 中〕/Ding Xuejun, Feng Huiwen (Central China University of Science & Technology), Hu Pingfang (Wuhan Municipal Construction Institute)//Journal of Engineering for Thermal Energy & Power. —1999, 14 (2). —102~105

Described in this paper are the specific features of a multi—pressure condenser and its energy—saving fundamentals. An analysis is given of the application prospects of such condensers in 200 MW units. A triple—pressure condenser has been designed with its energy—saving effectiveness calculated. In addition, the authors also discussed the possibility of modification of a condenser to triple—pressure for a 200 MW unit currently in operation. It is shown that the use of triple—pressure condensers in a region with a high water temperature or in the case of a cooling tower being employed can lead to an enhanced economical operation of the power plants. **Key words**: multiple—pressure condenser, steam turbine, economy

管内强化对流换热的热力经济性分析=**Thermodynamic Performance Analysis of In—tube Intensified Convection Heat Transfer**〔刊, 中〕/Wu Huiying (Shanghai Jiaotong University), Shu Fang (Nanjing Architectural Engineering Institute)//Journal of Engineering for Thermal Energy & Power. —1999, 14 (2). —106~107

In the light of the simultaneous increase of in—tube heat transfer and resistance the authors on the basis of Webb's index performed an evaluation of the complex thermodynamic performance of heat transfer and flow re-

sistance under the conditions of in－tube intensified convection heat transfer. Thus obtained are functional relations between thermodynamic performance indexes Q/Qs, P/Ps and F/Fs on one side and in－tube convection heat transfer Nu and in－tube resistance factor l on the other side. On this basis an analysis was conducted of the thermodynamic performance of the intensified in－tube heat transfer inside spirally corrugated tubes. **Key words**: intensified in－tube heat transfer, convection heat transfer, thermodynamic performance, spirally corrugated tube

高效液力偶合器的设计方法分析＝**The Design Method and Analysis of a High－efficiency Fluid Coupling**〔刊, 中〕/Wang Liwen, Li Guohong, Li Rong (China National Civil Aviation Institute) //Journal of Engineering for Thermal Energy & Power. －1999, 14 (2). －108～110

The problem of excessive heat generation in a high－capacity (＞300 KW) fluid coupling was resolved by the use of a high－efficiency coupling with a no－slip feature at rated operating conditions. This paper analyses the design method of such a coupling with the method for determining the number of buckets and bucket wheels being proposed. Furthermore, through tests of a sample unit the features of the coupling are identified. **Key words**: high－efficiency fluid coupling, bucket, bucket wheel, design method, test of characteristics

盘管式蓄冰空调系统评价＝**Evaluation of an Coiled－Tube Ice Storage Air－conditioning System**〔刊, 中〕/Zhou Wei, Yin Gang, Liao Mingyi, et al (Heilongjiang Provincial Commercial Institute) //Journal of Engineering for Thermal Energy & Power. －1999, 14 (2). －111～112

Four schemes of coiled－tube ice storage air－conditioning systems are presented in this paper with an analysis and comparison being conducted by the use of specific examples. It is noted that all these four schemes are economically feasible. The one based on a direct evaporation of refrigerant and low－temperature air supply system enjoys the best economy. Compared with a conventional system its peak－clipping rate is 40% with investment cost and operating expenses being reduced respectively by 15% and 48%. **Key words**: cold storage rate, ice storage air－conditioning system, electric tariff structure

SAYVOL－EC2燃油全能增效剂掺入重油在燃气轮机上的燃烧试验＝**Heavy Oil－fired Gas Turbine Combustion Test with the Heavy Oil being admixed with SAYVOL－EC2 All－purpose Fuel Oil Synergist**〔刊, 中〕/Liu Ming, Wen Xueyou, Chen Hongfa (Harbin No. 703 Research Institute) //Journal of Engineering for Thermal Energy & Power. －1999, 14 (2). －113～118

SAYVOL－EC2 all－purpose fuel oil synergist is a product developed by British Sayvol Chemicals Ltd. Combustion tests were conducted on a gas turbine combustion test rig, firing heavy oil admixed respectively with conventional magnesium salt vanadium inhibitor and SAYVOL－EC2 additive. Test results indicate preliminarily that the SAYVOL－EC2 all－purpose fuel oil synergist is superior to the conventional magnesium salt vanadium inhibition agent in terms of combustion efficiency, vanadium inhibition effectiveness, NOx reduction, etc. **Key words**: synergist, vanadium inhibition, heavy oil combustion, gas turbine

适用于舰用汽轮机的准三维设计体系＝**A Three－dimensional Design System Applicable to Naval Steam Turbines**〔刊, 中〕/Huang Hongyan, Feng Guotai, Wang Zhongqi (Harbin Institute of Technology), Ma Yunxiang, Lin Zhihong, Wen Xueyou (Harbin No. 703 Research Institute) //Journal of Engineering for Thermal Energy & Power. －1999, 14 (2). －119～121

A naval steam turbine design system has been set up based mainly on a multi－stage S_2 stream surface calculation and assisted by a S_1 stream surface calculation program and single－row cascade full three－dimensional Euler equation solution program. In the S_2 stream surface calculation a variable specific heat is taken into account with a loss model being introduced. This is done so that the machine efficiency can be evaluated in a relatively accurate way and a matching calculation of the steam turbine both in terms of interstage as well as between rotating blades and stator vanes may be performed. The S1 stream surface and three－dimensional viscous and non－viscous calculation programs can be employed to verify and check cascade space flow passage performance. The system under discussion is suited for the naval steam turbine verification calculation and performance analysis for off