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储冰桶换热管组流动特性研究

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摘 要: 分析了储冰桶换热器管组的流动过程, 建立实际流动的物理模型, 通过理论推导, 获得了分析解。为准确计算换热器管组流量分布、系统压降以及设计提供一种理论方法。

关 键 词: 储冰桶; 换热器; 流动特性; 流量分布论; 压降

中图分类号: TB61^{+}1 文献标识码: A

引言

乙二醇溶液盘管式储冰桶在冰蓄冷空调系统工程中已有广泛应用。目前, 虽然有不少专家学者对储冰桶蓄冰和融冰过程进行理论分析和产品设计计算, 但尚欠完善, 还未见对换热管组的流量分布不均匀性分析和储冰桶压降进行理论分析。这对产品结构优化设计和系统工程设计有很大影响, 同时也影响储冰桶的容量、蓄冷率和放冷率等参数的准确计算。因此, 本文从实际过程出发, 对换热管组的流动特性进行理论上探讨。

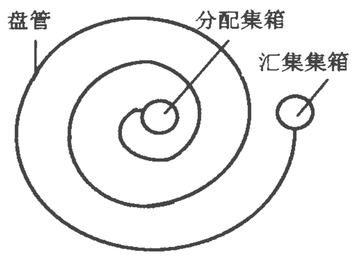

图 1 换热盘管示意图

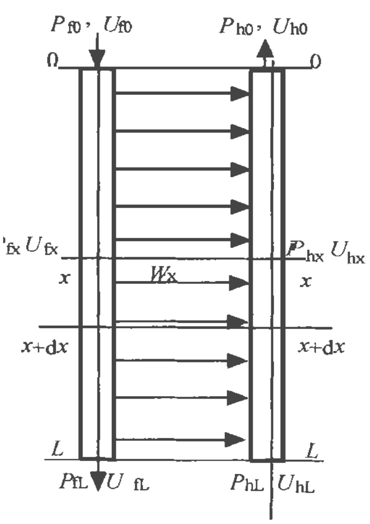

图 2 U 型联箱连接系统

1 乙二醇溶液盘管式储冰桶结构

乙二醇溶液盘管式储冰桶结构的外部是圆柱形双层敞口壳体, 顶部是可移动的顶盖; 内部是相互平行多层管组, 单根换热管成阿基米德螺线形, 放置于桶体内; 桶内盛满水, 乙二醇溶液在管内流动, 在蓄冷过程时, 制冷工况下运行的制冷机组产生低温乙二醇溶液经过换热管组, 把冷量传递给静止的管外水, 水逐渐凝固为冰; 在放冷过程时, 高温乙二醇溶液流经换热管组, 吸收冷量后和空调工况下运行的机组配合, 供冷量给空调场所, 管外的冰又逐渐融化为水。其结构如图 1、图 2 所示。

2 物理模型建立

由储冰桶的结构可知, 乙二醇溶液从单一端口进入分配集箱, 在集箱中分别流进相互平行的盘管, 然后在汇集集箱中从单一端口流出。要计算各支管的流量, 一般流体力学课本中介绍的并联管路算法已不适宜此过程的计算。为解决储冰桶换热管组的流量分配计算问题, 本文作者经查阅大量有关资料, 作出下述探讨。

2.1 结构参数与假设

分配集箱单端轴向引入单相流体, 流通截面积恒定为 F_f、长度为 L; 单根支管流通截面积为 F_1, 长度为 l, 支管总数为 m; 汇集集箱流通截面积为 F_h、长度为 L。

并联管组沿分配集箱轴向和汇集集箱轴向均匀布置; 忽略工质密度沿集箱轴向和支管轴向的变化; 忽略分配集箱与汇集集箱内流体的沿程摩阻; 忽略盘管弯曲阻力。

2.2 方程组的建立

2.2.1 分配集箱

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集箱内轴向满足能量方程, 根据水动力计算方法[1]:

$$P_{fx} - P_{f0} = \frac{1}{2}\rho n_f(u_{f0}^2 - u_{fx}^2) + \rho g x \tag{1}$$

式中: p 为压力, ρ 为乙二醇溶液的密度, n 为动、静压转换系数, u 为分配集箱中溶液速度, g 为重力加速度; 下标 f 表示分配集箱, x 为 x 轴坐标, 0 表示分配集箱进口。

从分配集箱到支管末端满足的能量方程为:

$$P_{fx} + \frac{1}{2}\rho u_{fx}^2 = p_{fxl} + \frac{1}{2}\left[\xi_{fx} + \frac{\lambda l}{d_1}\right]\rho w_x^2 \tag{2}$$

集箱对支管分流过程满足的连续性方程:

$$\mathrm{d}u_{fx} = -S_f w_{fx}\mathrm{d}x \tag{3}$$

式中: p_{fxl} 表示支管位于沿流程末端的压力, w 为支管液体流速, $S_f = mF_1/F_fL$, λ 为支管沿程阻力系数, 分流阻力系数 ξ_{fx} 是支管内入口的流速与当地集箱内轴向平均流速之比 (w_x/u_{fx}) 的函数, 通过分析研究, 其具有如下形式:

$$\xi_{fx} = \frac{a_f}{(w_{fx}/u_{fx})^2} + b_f \tag{4}$$

式中: a_f、b_f 是支管与分配集箱的直径比 (d_1/D_f) 和连接方式决定的常数。当 $d_1/D_f = 0.10 \sim 0.15$ 时, $a_f = 1.0$, $b_f = 0.5 \sim 0.8$; $d_1/D_f \leqslant 0.1$, $a_f = 1.0$, $b_f = 0.5$[1]。

2.2.2 汇集集箱

同理, 推出汇集集箱的压力分布表达式,

$$P_{hx} - P_{h0} = \frac{1}{2}\rho n_h(U_{h0}^2 - U_{hx}^2) + \rho g x \tag{5}$$

$$P_{fxl} + \frac{1}{2}\rho w_x^2 = P_{hx} + \frac{1}{2}\rho\xi_{hx}u_{hx}^2 \tag{6}$$

$$\mathrm{d}u_{hx} = S_h w_x \mathrm{d}x \tag{7}$$

$$\xi_{hx} = \frac{a_h}{(w_x/u_{hx})^2} + b_h \tag{8}$$

式中: L 为汇集集箱的长度; n_h 为汇集集箱动静压转换系数; a_h、b_h 是支管与汇集集箱的直径比 (d_1/D_h) 和连接方式决定的常数。一般地, 可取 $a_h = 1.10 \sim 1.25$, $b_h = -1$。下标 h 表示汇集集箱, x 为 x 轴坐标, 0 表示汇集集箱出口。

2.2.3 边界条件

$$x = 0,\ u_{fx} = u_{f0},\ u_{hx} = u_{h0} \tag{9}$$
$$x = L,\ u_{fL} = 0,\ u_{hL} = 0$$

2.3 微分方程组求解

2.3.1 微分方程组的解

联立方程式并整理得:

$$\rho(n_f - b_f - 1)\frac{u_{fx}^2}{2} + \rho E\frac{w_x^2}{2} = \rho(n_h - b_h - 1)\times\frac{u_{hx}^2}{2} + p_{f0} - p_{h0} + \frac{\rho n_f u_{f0}^2}{2} - \frac{\rho n_h u_{h0}^2}{2} \tag{10}$$

式中: $E = a_h + b_f + \frac{\lambda l}{d_1}$

对式(10)进行两次微分, 经整理可得:

$$\frac{\mathrm{d}^2 w_x}{\mathrm{d}x^2} - \frac{(S_hL)^2(n_h - b_h - 1) - (S_fL)^2(n_f + a_f - 1)}{E}w_x = 0 \tag{11}$$

即可写成如下形式:

$$\frac{\mathrm{d}^2 w_x}{\mathrm{d}x^2} - Aw_x = 0 \tag{12}$$

式中: $A = [(s_hL)^2)(n_h - b_h - 1) - (S_fL)^2(n_f + a_f - 1)]/E$

显然, 式(12)是二阶常系数齐次微分方程, 其解有三种情况:

$$当\ A > 0,\ w_x = C_1 e^{\sqrt{A}x} + C_2 e^{-\sqrt{A}x} \tag{13}$$

$$当\ A = 0,\ w_x = C_3 + C_4 x \tag{14}$$

$$当\ A < 0,\ w_x = C_5\cos(\sqrt{-A}x) + C_6\sin(\sqrt{-A}x) \tag{15}$$

2.3.2 方程组解中的待定系数的值

常微分方程(12)的解中待定系数可以通过边界条件, 并结合流量平衡方程 $\int_0^L w_x \mathrm{d}x = \frac{u_{f0} - u_{fL}}{S_fL}$, 消去进口和出口的静压参数, 最终可得:

$$C_1 = \frac{1}{2}\left[\frac{u_{f0}}{S_fL}\frac{\sqrt{A}}{e^{\sqrt{A}} - 1} + \frac{S_fL}{u_{f0}}\frac{B}{\sqrt{A}(e^{\sqrt{A}} + 1)}\right] \tag{16}$$

$$C_2 = \frac{1}{2}e^{\sqrt{A}}\left[\frac{u_{f0}}{S_fL}\frac{\sqrt{A}}{e^{\sqrt{A}} - 1} - \frac{S_fL}{u_{f0}}\frac{B}{\sqrt{A}(e^{\sqrt{A}} + 1)}\right] \tag{17}$$

$$C_3 = \frac{1}{2} B \frac{S_f L}{u_{f0}} \quad (18)$$

$$C_4 = \frac{u_{f0}}{S_f L} - \frac{1}{4} B \frac{S_f L}{u_{f0}} \quad (19)$$

$$C_5 = \frac{1}{2}\left[\frac{u_{f0}}{S_f L} \sqrt{-A} + B \frac{S_f L}{u_{f0}} \frac{1}{\sqrt{-A}} \right] \quad (20)$$

$$C_6 = \frac{1}{2}\left[\frac{u_{f0}}{S_f L} \frac{\sqrt{-A}\sin\sqrt{-A}}{1-\cos\sqrt{-A}} + B \frac{S_f L}{u_{f0}} \frac{1-\cos\sqrt{-A}}{\sqrt{-A}\sin\sqrt{-A}} \right] \quad (21)$$

以上式中：

$$B = \frac{(n_f + a_f - 1) u_{f0}^2 - (n_h - b_h - 1) u_{h0}^2}{E} \quad (22)$$

2.4 换热管组的流动特性

2.4.1 换热管组的流速分布

由以上推导可知，根据换热管组的有关参数计算，换热管组之间的流速分布即可选用表达式(13)(14)(15)计算。

2.4.2 换热管组系统的压降

由 $x=0$ 时，初始值 u_{f0}，u_{h0}，w_0 代入式(10)，可导出换热管组系统的压降计算公式：

$$\Delta p = p_{f0} - p_{h0} = \frac{1}{2}\rho[(a_f - 1)u_{f0}^2 + (b_h + 1)u_{h0}^2 + E w_0^2] \quad (23)$$

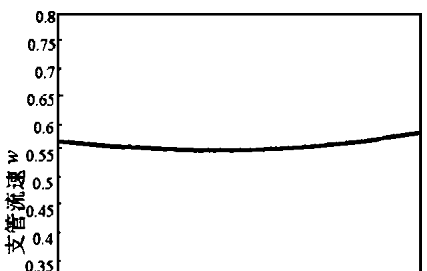

图 3 支管流速随集箱长度分布曲线

2.4.3 换热管组间的流量偏差

换热管组间的流量偏差定义为单根管中的质量流量与平均工况管中的质量流量之比。因各盘管直径相同、管中液体密度相同，所以即为管中的流速之比，即：

$$\eta_Q = \frac{w_x}{\bar{w}} = \frac{S_f L w_x}{u_{fo}} \quad (24)$$

3 计算实例

实例为南京安纳特有限公司 ET 储冰桶，其结构尺寸如下：分配集箱内径 0.065 m，分配集箱长度 2.0 m，支管直径 0.019×2，支管间距 0.045 m，支管根数60，支管长度60.0 m，汇集集箱内径0.065 m，汇集集箱长度 2.0 m。

计算中有关参数数据如下：

$n_f = 0.8$，$a_f = 1.0$，$b_f = 0.8$；$n_h = 2.0$，$a_h = 1.25$，$b_h = -1$。

据本模型计算，管组支管中液体流速分布如图3，最小流量偏差是 97.2%，最大流量偏差是 102.7。换热管组的系统压降为 0.03 MPa，与产品试验数据相差7%。

4 结论

乙二醇溶液盘管式储冰桶是较为常见的管外完全结冰的结构型式。本文从实际流动过程出发，通过理论推导，采用有关的处理方法，最后导出理论计算公式。通过实例计算，计算结果与产品试验数据相吻合。据大量计算发现，在储冰桶设计工作中，集箱和支管的直径、长度的选择对流量分布、压降和传热特性影响很大，应综合考虑。所以，对储冰桶的设计、冰蓄冷空调系统设计和系统模拟，本文提供一定的理论和实际参考价值。

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（渠 源 编辑）

Described in this paper is a new type of high temperature air-fired boiler featuring the following key techniques: high-temperature air combustion, a ceramic honeycomb heat storage bed, a burner adapted for graded burning of fuel, in-furnace re-circulation of flue gases and a four-way high-frequency switch-over valve. The boiler working principle and process was explained in detail and the basic innovative approach for further development of the boiler explored along with an analysis of its main technical characteristics. In addition, the authors have also assessed the potential significance of popularizing this new type of boiler in China. **Key words**: high-temperature air combustion, new type of boiler, heat exchanger, burner, analysis of characteristics

移动颗粒层过滤高温除尘器中循环清灰系统的试验研究＝**Experimental Study of a Pneumatic Conveyor-based Ash-removal System for a High-temperature Precipitator Featuring a Moving Granular Bed Filter** [刊, 汉] / XU Shi-Sen (Thermotechnical Research Institute of China National Electric Power Corporation, Xi'an, Shaanxi, China, Post Code 710032) // Journal of Engineering for Thermal Energy &Power. —2000, 15(4). —352～355, 363

Described in this paper is a pneumatic-conveying and filtrating media-based ash removal system capable of uninterrupted steady and high-efficiency operation. An experimental study aimed at structure optimization has been performed of the granular media feeding device, a transport system and the ash removal device. The operation experience of the above-cited ash removal system demonstrates the feasibility of a continuous and stable process of pneumatic-conveyor-based ash removal. The detailed information presented in the paper can serve as helpful hints and valuable reference data for the development of high-temperature ash removal technology based on the use of a moving granular bed filter. **Key words**: moving granular bed filter, pneumatic cycle ash removal, high-temperature dust elimination

混煤热天平燃烧模型研究＝**A Study of Thermobalance Model for the Burning of Blended Coals** [刊, 汉] / ZHANG Xiao-jie, NIE Qi-hong, SUN Shao-zeng, ZHU Qun-yi, WU Shao-hua, QIN Yu-kun (Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(4). —356～359

Each coal component in blended coals will keep its individual combustion characteristics during the combustion process. On this basis set up is a thermogravimetric combustion model of blended coals. The results obtained from the model are in fairly good agreement with those of experimental tests. **Key words**: blended coals, combustion, model, thermobalance

油田火筒加热炉大开孔封头强度研究＝**A Study of the Strength of a Crude Oil Heating Boiler Head Perforated by Large Openings** [刊, 汉] / WANG Huai-bin, XING Zhi-dong, DU Jun, *et al* (College of Energy Science and Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. —2000, 15(4). —363～363

At present there exist no applicable standards or specifications for calculating the strength of crude oil heating boiler (COHB) heads perforated by densely distributed large openings. This has to a certain extent hampered the further development of crude oil heating boilers in China. In this paper a finite-element strength analysis and calculation for the following three types of boiler head perforated by large openings is performed with the help of a plate-shell model: i.e., one without any reinforcement, another one with a reinforcement and a third one with a cross-shaped reinforcement. The results of a theoretical and experimental study indicate that the finite-element model set up by the authors is feasible and effective for the strength analysis of boiler heads perforated by large openings. The calculation results agree quite well with those obtained through tests. The actual stress sustained by the heads has not surpassed the allowable stress of the relevant material used. **Key words**: head, strength, large openings, finite-element analysis, experimental study, heating boiler

储冰桶换热管组流动特性研究＝**A Study of the Flow Characteristics of a Heat Exchange Tube Bank in an Ice Storage Tank** [刊, 汉] / QIAN Huan-qun, MIAO Zheng-qing, HU Zhi-hua, *et al* (Xi'an Jiaotong University, Xi'an,

Shaanxi, China, Post Code: 710049) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —364 ~366

An analysis was performed of the flow process of a heat exchange tube bank in an ice storage tank, and a physical model featuring the actual flow process has been set up. An analytical solution was obtained through a theoretical deduction. On the basis of the above the authors have provided a theoretical method for the accurate calculation of the flow distribution and system pressure drop of the heat exchange tube bank as well as the design of the latter. **Key words**: ice storage tank, heat exchanger, flow characteristics, flow distribution, pressure drop

非线性刚性转子—轴承系统的混沌研究= **A Study on the Chaotic Motions Existing in a Nonlinear and Rigid Rotor-bearing System** [刊, 汉] /ZHANG Xin-jiang, WU Xin-hua, HAN Wan-jin (College of Energy Science and Engineering under the Harbin Institute of Technology), LI Jian-zhao (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —367 ~369

In connection with the specific features of a nonlinear rotor-bearing system and under a relatively wide range of parameters a study has been conducted of the stability of a rigid Jeffcott rotor-bearing system using a short bearing model. The study was performed on the basis of the rotor dynamics and nonlinear dynamics theory and with the use of a numerical integration and Poincaré mapping method. The results of calculation show that there exist chaotic motions in the above-mentioned system. With the help of a numerical method obtained in some parameter domains of the system were the following: bifurcation diagrams, response curves, time histories, frequency spectrum and phase diagrams, shaft centerline locus and Poincaré mapping diagram. All the above gives a visual display of the operating condition of the system in some parameter domains. Meanwhile, an analysis was conducted of the effect of the bearing geometric dimensions on the stability of the system. The results of the numerical analysis can provide a theoretical basis for the design and safe operation of this type of rotor-bearing system. **Key words**: rotor dynamics, nonlinearity, rotor-bearing system, chaotic motion, stability

重载低速动压润滑推力轴承的理论分析= **Theoretical Analysis of a Dynamic-pressure Lubricated Heavy-duty and Low-speed Thrust Bearing** [刊, 汉] / LI Jian-ping, LIU Rui (Harbin Boiler Co. Ltd., Harbin, China, Post Code: 150046) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —370 ~372

A theoretical analysis was conducted of a multiple-slide pad and plane thrust bearing with respect to such a variety of parameters as elastic deformation, load-bearing capacity, rigidity, oil viscosity and oil film thickness, etc. Some of the relationships governing these parameters, thus obtained, can serve as a theoretical basis for the rational design of the above-cited bearing. **Key words**: elastic deformation, dynamic pressure lubrication, oil film thickness

三压再热汽水系统 IGCC 的设计工况和变工况性能= **Design and Off-design Performance of the Integrated Gasification Gas-steam Combined Cycle (IGCC) of a Triple-pressure Reheat Steam-water System** [刊, 汉] / LU Ze-hua, ZHAO Shi-hang, SHANG Xue-wei, CAO Ren-feng (Qinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —373 ~375

With the integrated gasification gas-steam combined cycle (IGCC) of a triple-pressure reheat steam-water system serving as an object of study proposed in the present paper is the design scheme of an integrated air separation IGCC system. Set up was a mathematical model involving the following units: a gasification furnace, a purification system, a gas turbine, an air separation unit, a heat recovery boiler and a steam turbine. A series of calculations were performed of both the design and off-design performance of the IGCC system. Analyzed was the effect on the system off-design performance in the case of the gas turbine adopting different control and regulation laws as well as in the case of the steam turbine assuming different operational modes. In addition, a rational operational mode has also been proposed. **Key words**: integrated gasification gas-steam combined cycle, integrated air separation unit, off-design operating conditions, regulation law and