

## 腔体式吸收器与真空管吸收器的热性能比较

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〔摘要〕本文分析了槽形抛物镜聚光集热器中管簇结构和环套结构的腔体式吸收器以及真空管吸收器的热物理特征,画出其热阻网络,建立太阳能一般性控制方程,并以此为依据对这三种吸收器的热性能进行了数值分析比较。

关键词 太阳能 吸收器 热效率

分类号 TK531

## 0 前言

在中温太阳能热利用中,槽形抛物面聚焦集热器占有重要的地位。这种集热器的吸收器可分为腔体式吸收器和真空管吸收器两种,腔体式吸收器依据结构特征又可分为管簇结构和环套结构两种。有必要对真空管及两种腔体式吸收器作出热性能分析比较。

## 1 三种吸收器的热物理特征及其热阻网络

## 1.1 真空管吸收器

真空管吸收器为一置于同心玻璃管内的金属圆管,其外表面涂有光谱选择性涂层,夹层抽真空以最大限度地减少对流热损。

真空管吸收器的优点为:吸收管无对流热损,有选择性涂层,对阳光的吸收率很高,而在其工作温度下的发射率很低。其缺点为:为保持长期高真空及选择性涂层的稳定性,工艺复杂,成本高,较大的流通断面造成工作流体的雷诺数较低,即从管壁至流体的换热

系数较低,加之吸热管上的热流密度大,故造成管壁与工作流体的温差加大,导致了热损较大<sup>[2]</sup>。

真空管吸收器的原理图和热阻网络图分别见图 1 和图 2。图 2 中,  $\phi_0$  为吸收器所吸收的太阳能,  $T_{w,m}$  为吸收器在提供有用热流  $\phi_{u,m}$  及存在热损情况下管壁的平衡温度。吸收器通过辐射(热阻  $R_{00}$ ) 向玻璃管散热(热流  $\phi_r$ ), 使玻璃管表面温度达到  $T_{s,m}$ , 再通过对流(热阻  $H_s$ )、辐射(热阻  $R_s$ ) 向环境散热(散热热流为  $\phi_s$ )。图 2 中  $\phi_{00}$  代表玻璃管吸收的太阳能流。

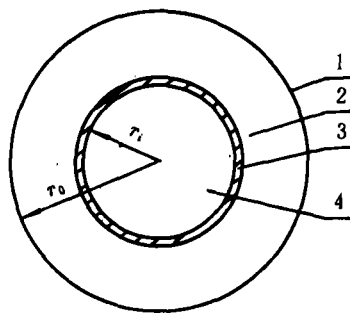


图 1 真空管吸收器结构图

1—玻璃管 2—选择性涂层 3—金属管 4—工质

收稿日期 1994—10—27 定稿 1995—01—25

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由图 2 可得确定热损总热阻的计算式

$$K_{tot} = R_{00} + \frac{1}{\frac{1}{R_s} + \frac{1}{H_s}} \quad (1)$$

### 1.2 腔体式吸收器

腔体式吸收器为一槽形腔体，外表面裹以隔热材料；由于腔体的黑体效应，使其能充分吸收聚焦后的阳光。

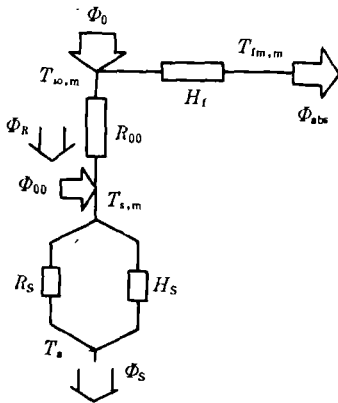


图 2 真空管吸收器热阻网络图

腔体式吸收器的优点为：经聚焦的辐射热流几乎均匀地分布在腔体内壁，与真空管吸收器相比，具有较低的投射辐射能流密度，也使开口的有效温度降低，从而使热损降低，因此腔体式吸收器在同样工况下吸收器效率一般优于真空管吸收器<sup>(2)</sup>；腔体式吸收器既无需抽真空，也无需涂光谱选择性涂层，只需传统的材料和制造技术便可生产，同时也使其热性能容易长期维持稳定。管簇结构见图 3，环套结构见图 4。

O. A. BARRA 等人设计的管簇结构腔体式吸收器，其结构特征在于管簇和腔体内壁不相联，由于腔体开口对管簇的角系数不足 0.5，因此聚焦后的大部分阳光直接照射到腔体内壁；而内壁由于不象管簇那样有介质流过可将吸收的热量带走，这就使得内壁的温度必然很高，导致吸收器热损较大。为改进，我们采用使管簇和腔体壁紧密联结的结构形式（例如焊接、胀接等方式，见图 3），让腔体壁不仅作为壳体，同时也成为管子间的翅片，使其吸收的热量可通过导热方式传递给管中的流动介质，同时也降低了腔体壁的温度，减

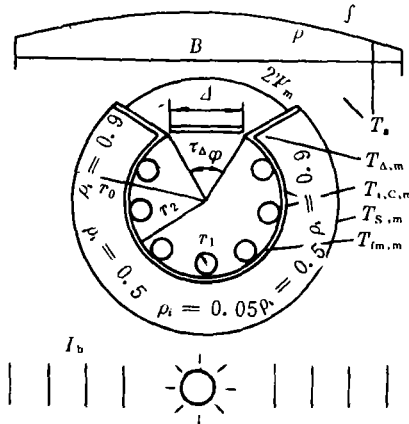


图 3 管簇结构腔体式吸收器的原理图

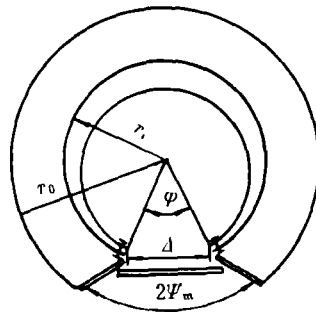


图 4 弯月形断面的腔体式吸收器结构

少通过保温层的热损。而腔体壁的导热作用也会对不同管子起到均温作用。我们采用由对可见光透过率很高,对热辐射反射率高(因而发射率低)的热镜作为腔体复盖窗。

上述两种腔体式吸收器的热阻网络如图5所示。其中,  $\Phi_{so}$  为腔体式吸收器内表面所吸收的太阳能,  $T_{ico,m}$  为吸收器内表面在向管簇中流过的工作介质提供有用热流  $\Phi_{sin}$  及存在热损情况下达到的平衡温度, 热损中一部分是通过传导(热阻  $K_{coa}$ )、对流(热阻  $H_{coa}$ )、辐射(热阻  $R_{coa}$ ) 向热镜窗散热, 使其温度达到  $T_{\Delta,m}$ , 再通过对流(热阻  $H_s$ )、辐射(热阻  $R_s$ ) 向环境散热; 另一部分通过传导(热阻  $K_c$ ) 向保温层散热, 使其外表面温度达到  $T_{s,m}$ , 再通过对流(热阻  $H_s$ )、辐射(热阻  $R_s$ ) 向环境散热。图5中  $\Phi_o$  和  $\Phi_{\Delta}$  分别代表保温层外表面和热镜窗吸收的太阳能。

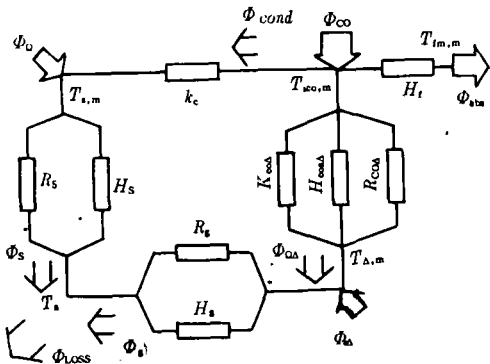


图5 管簇结构腔体式吸收器的热阻网络图

由图5可得确定热损的总热阻的计算式:

$$K_{tot} = \left\{ \left[ K_c + \frac{1}{\frac{1}{R_s} + \frac{1}{H_s}} \right]^{-1} + \left[ \frac{1}{\frac{1}{R_s} + \frac{1}{H_s}} \right] \right.$$

$$\left. + \frac{1}{\frac{1}{K_{coa}} + \frac{1}{H_{coa}} + \frac{1}{R_{coa}}} \right\}^{-1} \quad (2)$$

各项分热阻的计算可查阅参考文献[3]。

## 2 三种吸收器的热性能数值分析比较

### 2.1 太阳能集热器的一般性控制方程组

对吸收器表面写出能量平衡方程, 在稳态时, 有

$$\eta_{op} I_b F = \dot{m} C_p (T_{fm,o} - T_{fm,i}) + \frac{T_{ico,m} - T_a}{K_{tot}} \quad (3)$$

等式左边项代表吸收器接收的太阳能, 右边第一项代表工作介质带走的热量, 第二项代表吸收器的热损。式(3)及以后各式中出现的符号参见表1中的符号说明。对采用腔体式吸收器和真空管吸收器的槽形抛物镜集热器, 其光学效率  $\eta_{op}$  分别为:

$$\eta_{op腔} = \epsilon_0 \left[ 1 - \frac{2(r_1 + \delta)}{B} \right] f \rho \tau_{\Delta} \quad (4)$$

$$\eta_{op真} = \alpha_1 \left( 1 - \frac{2r_1}{B} \right) f \rho \tau_0 \quad (5)$$

式(4)中的  $\delta$  为腔体隔热层厚度;  $\epsilon_0$  为腔体式吸收器的有效黑度。上述各式构成太阳能集热器的一般性控制方程组。

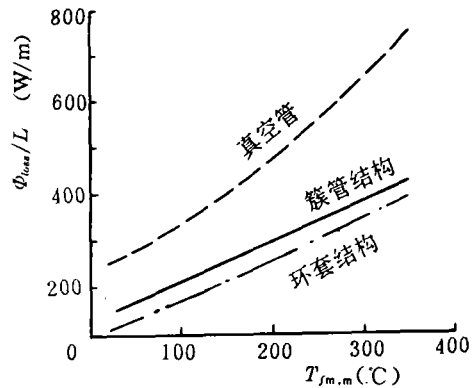


图6 各种吸收器的单位长度热损比较

集热器总效率和吸收器热效率的定义  
分别如下:

$$\eta_{tot} = \frac{\dot{m}C_p(T_{tm,o} - T_{tm,i})}{I_b F} \quad (6)$$

$$\eta_o = \frac{\dot{m}C_p(T_{tm,o} - T_{tm,i})}{\eta_{op} I_b F} \quad (7)$$

### 3 算例

#### 3.1 设计参数

表 1 槽形抛物镜及管簇结构  
腔体式吸收器设计参数

序号	项目名称	符号	单位	数值	备注
1	抛物镜开口宽度	$B$	m	4	
2	抛物镜或吸收器总长	$L$	m	5	
3	抛物镜焦距	$L_f$	m	1.80	
4	抛物镜聚焦比	$E$		40	
5	抛物镜焦平面或吸收器开口宽度	$d$	cm	10	
6	抛物镜方程				$Z = \frac{r^2}{4L_f}$
7	抛物镜开口半张角	$\psi_m$	°	58.1	
8	吸收器开口圆心角	$\varphi$	°	60	
9	吸收器腔体半径	$r_1$	m	0.1	
10	吸收器圆管根数	$n$		7	
11	吸收器圆管内径	$2r_1$	mm	15	
12	抛物镜光学修正系数	$f$		0.9	
13	抛物镜反射率	$\rho$		0.75	
14	腔体窗透过率	$\tau_\Delta$		0.9	
15	腔体内表面对可见光平均吸收率	$\epsilon_h$		0.5	
16	腔体内表面平均发射率	$\epsilon_{co}$		0.5	
17	腔体窗平均发射率	$\epsilon_\Delta$		0.07	
18	吸收器保温层外表面平均发射率	$\epsilon_s$		0.07	
19	玻璃纤维导热系数	$k_c$	W/(m·°C)	0.043	保温材料

续表 1

序号	项目名称	符号	单位	数值	备注
20	太阳直射辐射强度	$I_b$	W/m <sup>2</sup>	700	
21	室外空气温度	$T_a$	°C	25	
	有效天空温度	$T_{sky}$	°C	25	
	抛物镜表面温度	$T_c$	°C	25	
22	室外风速	$u_{am}$	m/s	5	
23	工作介质平均温度	$T_{tm,m}$	°C	295	
24	工作介质入口温度	$T_{tm,i}$	°C	293.5	
25	工作介质平均流速	$u_{tm}$	m/s	0.5	
26	太阳能集热器效率	$\eta_{tot}$	%	30	
27	太阳能集热器光学效率	$\eta_{op}$	%	40	
28	腔体式吸收器效率	$\eta_o$	%	50	

表 2 各种吸收器热性能比较时  
所选计算工况

吸收器类别	计算工况
腔体式吸收器	管簇结构 表 1 中所示的典型工况
	环套结构 1. $2r_i = 200 \text{ mm}, \delta = 5 \text{ mm}$ ; 2. 其余和典型工况相同。
真空管吸收器	① $2r_i = 100 \text{ mm}, 2r_o = 180 \text{ mm}$ $\tau_o = 0.9, a_i = 0.9$ ; ② $\epsilon_o = 0.8$ , $\epsilon_i = 0.1$ ; ③ $u_{tm} = 0.63 \text{ m/s}$ 。

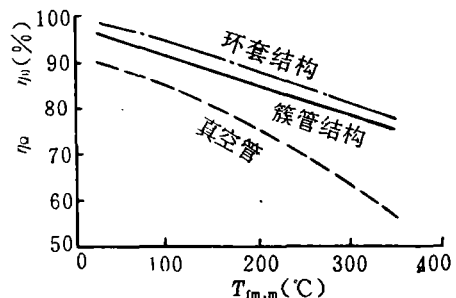


图 7 各种吸收器的吸收器效率比较

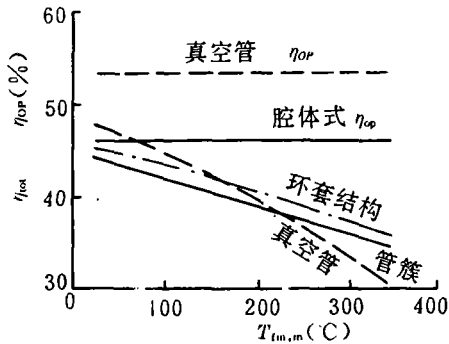


图8 各种吸收器的集热器效率比较

#### 4 结束语

如图6所示,各种吸收器的 $\phi_{\text{col}}/L$ 均随 $T_{\text{fm,m}}$ 增大而上升,真空管的热损大于管簇结构,这与文献[2]的结果相同,而管簇结构又大于环套结构;两种腔体的曲线接近于线性,而真空管则为非线性上凹曲线,当 $T_{\text{fm,m}}$ 大于 $130^{\circ}\text{C}$ 后,上升更显著。

如图7所示,两种腔体式和真空管吸收器,其吸收器效率均随 $T_{\text{fm,m}}$ 的增大而降低;环套结构的吸收器效率大于管簇结构,而管簇结构又大于真空管,两种腔体的曲线接近

于线性,而真空管为非线性下凹曲线,当 $T_{\text{fm,m}}$ 大于 $130^{\circ}\text{C}$ 后,下降更显著。

如图8所示,真空管集热器光学效率 $\eta_{\text{op}}$ 大于腔体式;各种吸收器对应的集热器总效率均随 $T_{\text{fm,m}}$ 增大而降低;在小于 $150^{\circ}\text{C}$ 时真空管的集热器总效率 $\eta_{\text{col}}$ 大于腔体式的,在大于 $230^{\circ}\text{C}$ 后,腔体式的集热器总效率 $\eta_{\text{col}}$ 大于真空管的;腔体式集热器总效率曲线接近于线性,而真空管则为非线性下凹曲线,在大于 $130^{\circ}\text{C}$ 后下降更显著;上述情况决定了真空管吸收器适合于低温工况下运行,而腔体式吸收器适合于中、高温工况下运行。

真空管吸收器和腔体式吸收器相比,热损较大,吸收器效率较低;但是由于其光学效率较高,从而导致两者的集热器效率在中、低温区段内有一相交点。

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## 发展核电势在必行

据有关方面消息,在本世纪末最后几年里,我国将有1000万千瓦核电动工兴建,其中广东大亚湾第二核电站、辽宁核电站已获得正式批准,预计将在“九五”末期开工。广东第二核电站拟选用法国 $2 \times 100$ 万千瓦核电机组,辽宁核电站本期工程拟选用俄罗斯 $2 \times 100$ 万千瓦成套核电设备,由中央和地方集资建设。其余浙江、山东、江苏、福建、湖南等地也在开展核电站的前期工作。有关专家认为,我国核电的高速发展阶段将在2010年前后出现,按照电力部制定的核电发展规划,到2010年,全国核电装机容量将达到2000~2300万千瓦,到2020年达到4000~5000万千瓦。

翅片形式对强化换热影响的研究及其效应评价=A Study of the Effect of Fin Shapes on Intensified Heat Exchange and the Evaluation of the Said Effect [刊,中]/Luo Zhongyang, Yin Chungeng, et al (Zhejiang University)//Journal of Engineering for Thermal Energy & Power. -1996,11(5). -257~261

An experimental study is conducted of the effects of fin shapes on convection heat exchange and flow characteristics. By combining the above two effects and on the basis of a thermodynamic system energy analysis an evaluation is made of the effectiveness of the various fin shapes on the intensified heat exchange. **Key words:** intensified heat exchange, heat exchange characteristics, resistance characteristics, entropy.

反切风消减锅炉烟道两侧烟气参数偏差的探讨=A Preliminary Study on the Reduction and Elimination of Flue Gas Parameters Deviation at Both Sides of a Boiler Gas Duct through the Introduction of Anti-tangential Air [刊,中]/Zhang Xuan, Xu Tongmo, et al. (Xi'an Jiaotong University)//Journal of Engineering for Thermal Energy & Power. -1996,11(5). -262~266

Through the cold-state model test of a high-capacity boiler obtained is the flow field distribution within the boiler and at the furnace outlet horizontal gas pass. An experimental study and analysis is conducted with respect to the reasons and governing laws of flue gas parameter deviation at both sides of the boiler gas duct caused by a remnant rotation with main focus on the mechanism of eliminating such a deviation by way of introducing anti-tangential air and the search for a rational version. This research work of the authors can provide useful guidance in eliminating excessively high temperature-related tube explosion failures of superheaters and reheaters caused by flue gas parameter deviations. **key words:** anti-tangential air, flue gas parameter deviation

角管式热水锅炉辐射受热面水动力特性分析=An Analysis of the Radiant Heating Surface Hydrodynamic Characteristics of a Corner-tube Hot-water Boiler [刊,中]/Ji Dezhong, Meng Zhaopeng, et al (Harbin Institute of Technology), Gao Xijiang (Heilongjiang Provincial Labor Bureau)//Journal of Engineering for Thermal Energy & Power. -1996,11(5). -267~271

This paper describes a method for calculating the hydrodynamic properties of the side water wall of a corner-tube hot-water boiler. An analysis is given of the effect of the flow rate of working medium entering a side-wall lower header on the water wall hydrodynamic characteristics. **Key words:** corner-tube hot water boiler, side water wall, hydrodynamic characteristics

腔体式吸收器与真空管吸收器的热性能比较=Comparison of Thermal Properties of Cavity Type Absorbers and Vacuum Tube Absorbers [刊,中]/Chou Qiaoli, Ge Xinshi, et al (China National University of Science & Technology)//Journal of Engineering for Thermal Energy & Power. -1996,11(5). -273~277

An analysis is performed of the thermo-physical characteristics of cavity type absorbers with tube bundle construction and ring-casing construction used in a parabolic solar energy collector as well as a vacuum tube absorber. The thermal resistance network in the said absorbers is shown in an illustration and the general control equation of the solar energy collector is also provided. Based on the above the authors have conducted a numerical analysis and comparison of the thermal properties for the above-cited

three types of absorbers. **Key Words:** solar energy, absorber, thermal efficiency

壳侧气液两相流沿水平方向横掠水平管束截面含气率的预测 = Prediction of Void Fraction of a Shell-side Gas-liquid Two-phase Flow along a Horizontal Direction Transverse Horizontal Tube Bundle [刊, 中]/Li Wei (Jiangsu Petrochemical Institute), Wang Qijie (Xi'an Jiaotong University) // Journal of Engineering for Thermal Energy & Power. -1996, 11(5). -278~281

On the basis of experimental investigation coupled with the research findings of veteran engineers the authors have duly modified a theoretical model for predicting average void fraction in tubes and proposed their own theoretical model for the prediction of the void fraction of shell-side gas-liquid dual-phase flow of a segmentally baffled shell-and-tube heat exchanger along horizontal direction transverse horizontal tube bank. It has been shown that the proposed model is able to make a quite accurate prediction of the average void fraction of different-matter dual-phase flow in shell-side in-line and staggered horizontal tube banks. **Key words:** shell-and-tube heat exchanger, gas-liquid two-phase flow, void fraction

斯特林热机的性能优化分析 = Optimal Analysis of a Stirling Heat Engine Performance [刊, 中]/Yuan Duqi, Liu Zongxiu (Baoji College of Arts & Science) // Journal of Engineering for Thermal Energy & Power. -1996, 11(5). -282~284

Taking into account the nonreversibility of thermal resistance in a Stirling heat engine working process, the finite time character of constant volume regenerative process and regeneration loss, the authors have conducted an optimal analysis of the Stirling heat engine performance under the Newton heat transfer law by employing finite time thermodynamics theory, and obtained some conclusions helpful for the optimal design and the selection of optimal working parameters. **Key words:** Stirling heat engine, heat transfer law, performance optimization, finite time thermodynamics.

缩放喷管内两相流动的数值模拟及喷管设计 = The Numerical Simulation of Two-phase Flow in a Convergent-divergent Nozzle and the Design of Such Nozzles [刊, 中]/Lu Zehua, Cao Renfeng (Tsinghua University) // Journal of Engineering for Thermal Energy & Power. -1996, 11(5). -285~291  
Described in this paper is a dual-fluid split-phase flow mechanism model with dual-phase relative drift and flow pattern transformation during non-equilibrium state phase transformation being taken into account. A numerical simulation was performed of the steam/liquid dual-phase flash evaporation critical flow within the convergent-divergent nozzle. A computation program has been worked out. The calculation results are in good agreement with experimental data. The nozzle design method has been successfully employed in the modification work of an energy-saving system of Yueyang Changling Refinery in Hunan Province. **Key words:** convergent-divergent nozzle, two-phase flow, flash evaporation, numerical simulation

EC301 压缩机扩容改造项目低压段离心级试验设计 = Test and Design of a Low-pressure Section Centrifugal Stage in Connection with EC 301 Compressor Uprating-oriented Modification Project [刊, 中]/Wang Dawei (Harbin 703 Research Institute) // Journal of Engineering for Thermal Energy & Power. -1996, 11(5). -292~296

The full-scale three-dimensional flow centrifugal stage test conducted on an axial compressor test rig