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蜂窝陶瓷蓄热体格孔壁面应力变化特性的数值研究

欧俭平[1], 蒋绍坚[1], 吴创之[2], 萧泽强[1]
(1. 中南大学 能源与动力工程学院, 湖南　长沙　410083; 2. 中国科学院 广州能源研究所, 广东　广州　510070)

摘　要: 介绍了高温空气燃烧过程中蜂窝陶瓷蓄热体的工作原理和损毁原因, 采用代数雷诺应力模型和修正的速度－压力耦合算法 SIMPLEC, 耦合蓄热体内流体的流动和换热过程, 运用有限元分析方法, 对蜂窝陶瓷蓄热体格孔壁面上的应力变化规律进行数值研究, 并根据计算结果对操作参数进行了改进。结果表明, 频繁的蓄热和释热过程变换, 使得蓄热体格孔壁面交替地受到拉应力和挤压应力的作用。流体的流速越大, 应力变化越大; 换向时间越短, 应力交替作用的影响越大。适当地调低烧嘴负荷, 延长四通阀的换向时间, 有利于提高蓄热体的使用寿命, 计算结果为蓄热体结构设计和操作参数的优化提供了依据。

关　键　词: 高温空气燃烧; 蜂窝陶瓷蓄热体; 应力; 疲劳破损; 有限元

中图分类号: TK223.3　　文献标识码: A

1　前　言

高温空气燃烧技术具有显著的节能环保效果, 被认为是 21 世纪的新燃烧技术, 而燃烧系统中的蓄热体则是这种燃烧技术的关键部件之一[1~2]。20 世纪 90 年代初, 日本工业炉株式会社田中良一领导的研究小组开始采用热钝性小的蜂窝型陶瓷蓄热体, 取得了很好的效果[1]。蜂窝型蓄热体在使用中, 由于格孔孔壁双面受热或冷却, 除受温度作用外, 还受各种应力作用, 很容易遭受损坏, 成为蓄热式高温空气燃烧技术应用推广的限制性环节。作者通过对国内数家企业生产现场被替换的蓄热体进行研究, 发现大部分蜂窝体单元出现不同程度的裂纹和剥落。显然, 脆性应力破裂是造成这一问题的主要原因。国内外对蜂窝陶瓷蓄热体的结构和传热特性已有了一定的研究[3~7], 但对于蓄热体所受应力的研究, 目前未见有文献报道。为了掌握它的应力特征和影响因素, 对蜂窝型蓄热体的寿命消耗进行控制, 确保蓄热体在设计的寿命期限内安全可靠的运行, 运用数值模拟的方法研究了蜂窝型蓄热体格孔壁面上的应力变化规律。考虑到蜂窝陶瓷蓄热体狭长的格孔孔壁对通道内气体流动的影响, 采用壁面函数法, 引入代数雷诺应力模型和修正的速度－压力耦合算法 SIMPLEC, 综合考虑蓄热体内的流体的流动和换热过程, 采用有限元分析方法进行计算。

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作者简介: 欧俭平(1970－), 男, 湖南邵阳人, 中南大学博士研究生。

2　蓄热体的工作原理

高温空气燃烧的蜂窝型蓄热室采用方孔蜂窝体砌筑而成。蓄热室的操作周期由加热期和冷却期组成, 其工作原理如图 1 所示。在加热期, 流过格孔的高温烟气将热量传递给蜂窝陶瓷蓄热体; 在冷却期, 低温的空气以相反的方向流过格孔并获得热量。

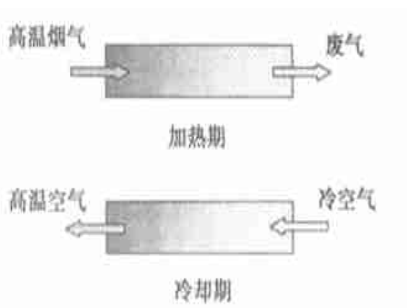

图 1　蓄热体工作原理图

3　数值模拟

3.1　计算模型及网格划分

以某厂现场实际使用的蜂窝型蓄热元件为对象, 其壁厚仅为 0.5 mm, 蜂窝单元间距为 3 mm。蓄热室长度为 600 mm, 每相邻 4 个格孔的中心连线围成一个正方形区域。如图 2 所示, 以该区域和沿蓄热室长度方向构成的三维空间内的蓄热体作为计算区域, 使用周期性边界, 为提高计算精度, 计算中对陶瓷蓄热体及气体界面处的单元进行了细致划分, 计算网格数为 44×15×15。

在高温空气燃烧过程中，蓄热体及流体的温度及受力周期性随时间而变化。为简化计算，假设：各格孔内的传热相同；忽略蓄热室的辐射换热和热损失；在蓄热体长度方向两个边界面温度只是时间的函数；流体的热物性参数恒定不变，蓄热体具有各向同性的导热特性，其比热是一个关于温度的多项式；蓄热介质的表面积及质量分布均匀；烟气与冷风在各自入口处的速度及温度在横截面上分布均匀，且不随时间变化；不考虑空气与烟气物性的差异对蓄热体特性的影响，在整个计算过程中都用空气作为传热介质。

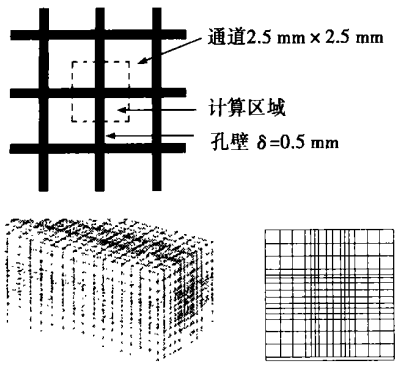

图 2 计算网格划分

3.2 控制方程组

对流体流动与传热的耦合过程，其模型可由下述控制方程组表示。

连续性方程：

$$\frac{\partial \rho_f}{\partial t} + \nabla(\rho_f U) = 0 \tag{1}$$

动量方程：

$$\frac{\partial \rho_f U}{\partial t} + \nabla(\rho_f UU) = -\nabla p'' + F_s + \nabla \pi_{ij} \tag{2}$$

π_{ij} 为 Reynolds 应力张量：

$$\pi_{ij} = \mu_{eff}\left[(\nabla U + (\nabla U)^T) - \frac{2}{3}(\nabla U) I\right] - \frac{2}{3}\rho_f k I \tag{3}$$

$$\mu_{eff} = \mu + \mu_T,\ \mu_T = C_\mu \rho_f \frac{k^2}{\varepsilon}$$

能量方程：

$$\frac{\partial p}{\partial t} = \frac{\partial \rho_f H}{\partial t} + \nabla(\rho_f UH) - \nabla\left(\left(\frac{\lambda_f}{c_{p,f}} + \frac{\mu_T}{\sigma_H}\right)\nabla H\right) \tag{4}$$

对于蓄热体的导热方程：

$$\frac{\partial \rho_s c_{p,s} T_s}{\partial t} = \nabla(\lambda_s \nabla T_s) \tag{5}$$

式中：ρ_f— 气体密度；U— 气体的速度矢量；P''— 修正压力；I— 单位矢量；F_s— 体积力；H— 总热焓；σ_H— 普朗特数；T_{ref}— 参考温度；$c_{p,f}$— 气体比热；λ_f— 气体导热率；C_μ— 湍流常数；μ、μ_T、μ_{eff}— 分别为气体的分子粘度、湍流粘度、有效粘度；ρ_s— 蜂窝陶瓷的密度；$c_{p,s}$— 蜂窝陶瓷的比热；λ_s— 蜂窝陶瓷的导热率；T_s— 固体温度。

3.3 边界条件和初始条件

进口采用 Dirichlet 条件，直接设定进口速度。考虑到在一个工作周期中蓄热和放热两个阶段具有相同的质量流量，但因冷热空气的温度差异，使得各自的进口流速差别很大，本文按表 1 所示工况确定进口条件。

表 1 主要计算工况表

工况	气体流速/ m·s⁻¹		气体温度差/ K
	加热期	冷却期	
1	30.0	7.5	970
2	20.0	4.5	970
3	10.0	3.0	970
4	20.0	4.5	1 170
5	20.0	4.5	770

由于蓄热式燃烧采用引风机抽引烟气，因此本计算采用压力边界条件，考虑到流体流过蜂窝型蓄热室的压降小于 1 000 Pa[1,3]，结合现场实际工况，计算中的出口压力均设为－800 Pa。

蓄热体壁面沿流动方向采用壁面函数，壁面内部无热源，温度变化由蓄热体的导热系数确定。

根据现场条件，整个计算区域内的初场设定为温度 305 K，速度为 0。考察一个工作周期流体入口速度、高低温气体入口温度差在不同的换向时间条件下对蓄热体壁面应力的影响，换向时间分别为 10 s、20 s、30 s、40 s、60 s 和 90 s。

4 计算结果及分析

计算结果表明，无论是加热期还是冷却期，蜂窝体格孔壁面主要受到法线方向的应力作用，其切向和轴向所受应力分别不到法向应力的 1/200 和万分之一。加热期应力指向壁面，对蓄热体孔壁产生挤压，表现为挤压应力；冷却期壁面受力方向指向流体，对壁面产生拉曳，表现为拉应力。显然，如果蓄热体的壁面所受应力大于其所能承受的最大应力，将导致应力脆裂。

4.1 气流速度对应力的影响

气体速度对应力的影响如图 3 所示。当入口气体温度差相同时，壁面所受的挤压应力和拉应力都

随着气流速度的增大而增大。这是因为, 气流速度的增大增加了气体的质量流量以及单位时间内气体对蓄热体的释热和吸热, 使得气体与蓄热体之间的热交换加快, 导致壁面受力增大。

4.2　冷热端气体入口温度差对应力的影响

在确定的气体流速下, 入口气体温度差对壁面所受压、拉应力的影响不如气流速度的影响明显(见图4)。这一方面是由于所选择的几种计算条件下温差的变化不大; 另一方面, 在蓄热体的工作过程中, 整个蓄热体具有长度方向的温度梯度, 尽管蓄热体的温度以一定的规律反复上升或下降, 但其高温端的温度始终高于低温端的温度, 因此温度的影响不同于一般意义上的急冷急热, 表现为入口气体温度差对应力的影响不大。

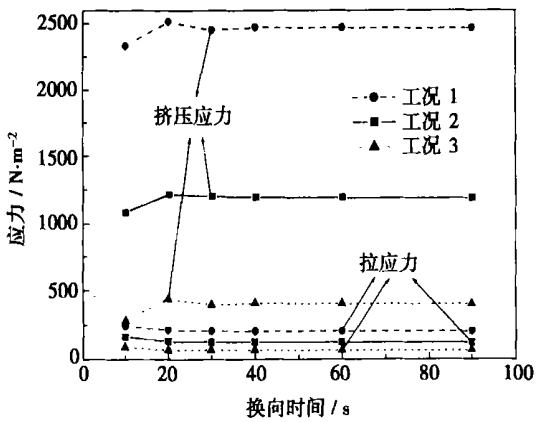

图 3　气流速度对应力的影响

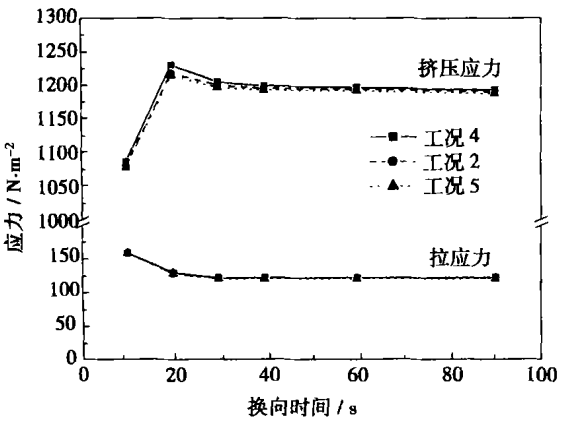

图 4　入口气体温度差对应力的影响

4.3　换向时间对应力的影响

图3 和图 4 表明, 当换向时间增大到一定值以后, 换向时间对应力本身的影响已不明显, 其对蓄热体使用寿命的影响主要体现为格孔壁面所受挤压应力和拉应力的交替作用的次数。换向时间越长, 压、拉应力的交替作用的次数越少, 越有利于蓄热体使用寿命的延长, 反之亦然。

5　实验验证

由计算得到的结果对国内某厂蜂窝型蓄热式烧嘴的操作参数进行了改进。根据工艺要求, 在可调节的烧嘴燃烧能力范围内, 适当地调低烧嘴的负荷, 延长四通换向阀的切换时间, 考察气体速度、入口气体温度差以及换向时间对蓄热体使用寿命的影响。实验结果表明, 采用改进措施后, 蓄热体的整体使用寿命从不到 2 个月延长到 5 个月以上, 达到了预期的效果。

6　结　论

(1) 频繁的蓄热和释热过程变换, 使得蓄热体格孔壁面交替地受到拉应力和挤压应力的作用。流体的流速越大, 应力变化越大; 换向时间越短, 蓄热体受拉应力和挤压应力交替作用的影响越大。

(2) 适当地调低烧嘴的负荷, 延长四通换向阀的换向时间, 有利于提高蓄热体的使用寿命。

(3) 数值研究的结果有利于实现生产现场的工艺操作参数的优化, 是指导热工设备设计和优化的重要手段。

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(何静芳　编辑)

surface the equivalent orientation emission rate in the zenith angle direction will increase. **Key words**: radiation heat transfer, Monte Carlo method, tube, equivalent orientation emission

分级燃烧对固体吸附剂吸附痕量金属的影响＝**The Impact of Graded Combustion on the Adsorption of Trace Metals by Solid Adsorbents** [刊, 汉] / HAN Jun, XU Ming-hou, ZENG Han-cai, et al (National Key Laboratory of Coal Combustion under the Huazhong University of Science &Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —52～55, 58

An experimental investigation was carried out in an one-dimensional pulverized-coal furnace to study the impact of graded combustion on the control by adsorbents of the emission of heavy metals. Through the investigation it was found that the graded combustion would increase the concentration of heavy metals in sub-micron particles, which is unfavorable for the control of trace heavy metals. This influence is especially significant in the case of highly volatile elements, such as copper and nickel. Solid adsorbents play an adsorption role with respect to the emission of heavy metals present in coal. Moreover, the adsorbents have a selective tendency in the adsorption of different heavy metals. In conclusion, the authors have expounded the mechanism of adsorption of heavy metal elements by the adsorbents. Such a mechanism is realized through both a physical and chemical adsorption, which coexist during a adsorption process. **Key words**: trace heavy metal, graded combustion, absorbent, coal combustion

催化重整反应对柴油掺水燃烧中着火的影响＝**The Influence of a Catalytic Reforming Reaction on the Ignition of Diesel Oil Mixed with Water** [刊, 汉] / WANG Chao, GONG Jing-song, FU Wei-biao (Department of Engineering Mechanics, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —56～58

The impact of a catalytic reforming reaction on the ignition temperature was investigated during the firing of diesel oil mixed with water. The focus of the investigation is on the change of ignition temperature when the catalytic reforming reaction takes place or not. From the results of experiments it can be seen that the catalytic reforming reaction has a significant influence on the ignition of emulsified diesel oil and can markedly reduce the ignition temperature. A detailed description is given of the experimental devices, test process and results along with circumstantial explanations and analyses. It is concluded that the catalytic reforming reaction can lower the ignition temperature of the emulsified diesel oil. Furthermore, two conditions essential for the implementation of catalytic reforming are also put forward. **Key words**: emulsified diesel oil, catalysis, reforming reaction, ignition

成型压力和炉膛温度对单颗粒型煤燃烧失重特性的影响＝**The Impact of Forming Pressure and Furnace Temperature on the Weight-loss Characteristics of Single-particle Briquette Combustion** [刊, 汉] / DONG Peng, JIANG Xue-hui, ZHAO Guang-bo (College of Energy under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —59～62

By making use of a thermogravimetric analysis method the weight-loss characteristics of single-particle briquette combustion were investigated. As a result, the laws governing the impact of forming pressure and furnace temperature on the weight-loss characteristics of single-particle briquette combustion have been deduced. In combination with a theoretical analysis a mathematical model was set up, which can reflect the mechanism of this influence. **Key words**: briquette, combustion, thermogravimetric analysis

蜂窝陶瓷蓄热体格孔壁面应力变化特性的数值研究＝**Numerical Study of the Stress Variation Characteristics at the Cellular-hole Wall-surface of a Honeycomb Ceramic Regenerator** [刊, 汉] / OU Jian-ping, JIANG Shao-jian, XIAO Ze-qiang (Institute of Energy &Power Engineering under the Zhongnan University, Changsha, China, Post Code: 410083), WU Chuang-zhi (Guangzhou Energy Source Research Institute under the Chinese Academy of Sciences, Guangzhou, China, Post Code: 510070) // Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —63～65

The operating principle and causes of damage of a honeycomb ceramic regenerator during high-temperature air combustion are described. By using an algebraic Reynolds-stress model and a revised speed-pressure coupled algorithm SIMPLEC a coupling of fluid flow and heat exchange process in the regenerator was implemented. With the help of a finite-element analysis method a numerical study of the stress variation law at the cellular-hole wall-surface of the honeycomb ceramic regenerator was performed. On the basis of calculation results operating parameters were improved on. It has been found that a very frequent switching-over of the process of heat accumulation and release will subject the cellular-hole wall-surface alternately to tension and extrusion stresses. The greater the fluid flow speed, the greater will be the variation of stresses. The shorter the direction-change time, the greater will be the influence of the stress alternating effect. A proper lowering of the load of burner nozzles and a prolongation of the direction-change time of a four-way valve will be conducive to increasing the service life of the regenerator. The calculation results can serve as a basis for the structural design of the regenerator and the optimization of the operating parameters. **Key words**: high-temperature air combustion, honeycomb ceramic regenerator, stress, fatigue failure, finite element

等离子发生器燃烧流场的数值模拟＝**Numerical Simulation of the Combustion Flow Field in a Plasma Generator** [刊, 汉] / ZHANG Ming-chang, LIU Min, CHEN Xiao-hong, et al (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —66～68, 80

The numerical simulation of a combustion flow field in a plasma generator was performed with the use of an eddy-breakage combustion model, a k - ε two-equation turbulence model and a SIMPLEC algorithm. As a result, a diagram was obtained, which shows the distribution of temperature fields, pressure fields and such parameters as turbulence pulsation kinetic-energy and its average dissipation rate, etc. **Key words**: plasma generator, numerical simulation, combustion, turbulence model, flow field

磁稳流化床除尘装置的设计与验证＝**Design and Experimental Verification of a Dust Removal Device for a Magnetically Stabilized Fluidized Bed** [刊, 汉] / WANG Ying-hui, GUI Ke-ting, SHI Ming-heng (Education Ministry Key Laboratory of Clean Coal Power Generation and Combustion Technology under the Southeastern University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy &Power. — 2004, 19(1). —69～72

The design method of a dust removal device for a magnetically stabilized fluidized bed is presented with a focus on the description of key component design. Meanwhile, an experimental verification was conducted of the major factors having an impact on the dust removal efficiency. The results of the experiments indicate that keeping the dust removal device in a magnetically stabilized state is a key factor for achieving high dust-removal efficiency. Other factors, such as bed layer thickness, gas apparent flow-speed ratio, etc also exert some influence on the dust removal efficiency. **Key words**: magnetically stabilized fluidized bed, dust removal, particle regeneration, dust removal efficiency

高温空气发生器冷态实验研究＝**Cold-state Experimental Research of a High-temperature Air Generator** [刊, 汉] / CAO Xiao-ling, WENG Yi-wu, LIU Yong-wen (Institute of Mechanical &Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), JIANG Shao-jian (Institute of Energy &Power Engineering under the Zhongnan University, Changsha, China, Post Code: 410083) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(1). —73～76

The necessity for developing a high-temperature air gasification system for biomass is expounded. For the research of high-temperature air gasification from biomass the authors have developed a key component, a high-temperature air generator experimental device, on which cold-state experiments were carried out. The results of the experiments indicate that the generator is capable of a normal and stable operation under cold-state experimental conditions. It is also possible to conduct further a hot-state experimental study. Through a cold-end regulation a divided flow of the high-temperature air can be realized. The flow rate and pressure at the outlet of the divided flow will gradually increase with an increase in the opening degree of a forced draft fan and a decrease in the opening degree of a fume exhaust fan. The quantity of high-