

# 里克型脉动燃烧技术工程化应用实验研究

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**[摘要]** 分析了直管形里克脉动燃烧器的缺陷,用两端收缩的办法成功地实现了燃烧室直径 1 米,长径比 4.5 的里克 -ZT 型脉动燃烧器燃烧脉动燃烧,初步解决了里克型脉动燃烧器的大型化问题

**关键词** 脉动燃烧 里克型脉动燃烧器 里克 -ZT 型脉动燃烧器

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## 1 引言

直管形里克脉动燃烧器是一个两端开口的  $1/2$  波长管,它结构简单,自身无需任何运动部件,是实现脉动燃烧技术工程实用化的一个理想选择对象。要使里克型脉动燃烧技术工程实用化,推向市场,就必须根据工业生产或日常生活需求,建造足够大尺寸的燃烧器。然而,据我们了解,目前国外最大的里克型脉动燃烧器直径约为 160 毫米,仅供实验用;国内虽有较大尺寸的里克型燃煤锅炉,但其燃烧室直径也只有 300 毫米,仅适用于小单位生活用途。建造更大尺寸的里克型脉动燃烧器以满足各种不同的需求,是该项脉动燃烧技术迈向工程化应用的关键。

## 2 大长径比要求制约了直管形里克脉动燃烧器的尺寸放大

里克型燃烧器是靠自激振荡产生并维持气体脉动的,这种自激是热声转换克服摩擦等造成的声能内部损失和辐射造成的声能外部损失,放大微弱扰动实现的。对于直管形里克管来说,管口向外辐射的声能是其主要损失项,若热声转换提供的声能小于管口损失的声能,自激脉动就不能实现。燃烧器的尺寸(如管长、管径等)和各尺寸之间的相互关系对声能的产生、损失以及最终能否实现定型脉动都有影响。因此,要建造大尺寸里克型脉动燃烧器并非轻而易举,不是把小尺寸燃烧器按比例简单放大就行了。

里克管或里克型脉动燃烧器本质上都是声学管。根据声学理论,只有管长  $L$  对管径  $D$  之比(即  $L/D$ ) 很大的管子才是声保持系统,即声能从管口泄漏很少。

管口的声阻抗可表示为

$$Z_l = R_l + iX_l \quad (1)$$

其中

$R_l = d_0 c \left[ 1 - 2 \frac{J_1(W)}{W} \right]$  是声阻;  $W = \frac{cD}{\lambda/2}$  是管口周长与半波长之比值;  $X_l = d_0 c M(W)$  是声抗;  $d_0$  是气体密度;  $c$  是声速;  $M$  是声质量;  $\lambda$  为波长。泄漏声功率可表示为

$$P_A = R_l \cdot U^2 \quad (2)$$

其中

$U$  是体积振速

因此,声阻是与声能从管口泄漏直接有关的参量。当  $W < 0.5$  即管口周长小于四分之一波长时,声阻  $R_l = \frac{d_0}{8c} D^2 k_0^2$ , 而  $k_0 = 2cf = \frac{c_0}{\lambda/2}$  是圆频率,直管形里克管的管长  $L \approx \lambda/2$ , 所以

$$R_l = \frac{c d_0 c^2}{8} \left[ \frac{D}{L} \right]^2 \quad (3)$$

从式(3)可以看出,长径比  $L/D$  越小,管口声能损失就越大。根据拉乌申巴赫的研究,为了在直管形燃烧器内激发声振, $L/D$  最好为 30~50; 通常文献资料报道认为  $L/D \geq 10$  即可。这么大的  $L/D$  极大地限制了直管形里克型燃烧器的尺寸放大。举例来说:燃烧器直径  $D = 0.6$  m, 高度就必须  $L \geq 6$  m, 而这样一台锅炉只有 0.2 t/h 的蒸发量。所以,较大的长径比要求制约了直管形里克脉动燃烧器直径的增大。

为了验证长径比对里克型自激脉动的影响,我们设计了直径  $D = 600$  mm 的燃煤直管形燃烧器,其管长和炉排位置均可调节,并进行了试验。当管长  $L = 3.8$  m ( $L/D = 6.3$ ) 时,实验表明该燃烧器已很难实现自激脉动。

## 3 两端收口的变截面里克型脉动燃烧器研究

大长径比的目的是为了减少声能在管口的损失,那么是否能不用大长径比设计而将管口收缩一点,以减少声能损失呢?

### 3.1 管内声波的透射和反射

当两端管口直径小于燃烧室直径形成台阶形截

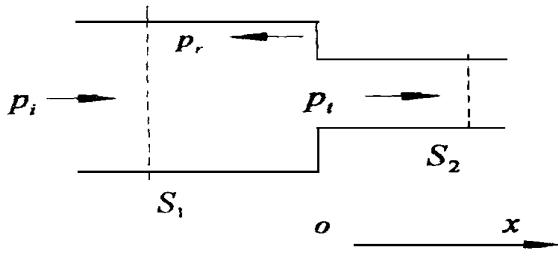


图 1 收缩截面的声波反射透射分析用图

面后,声波在管内的运动如图 1所示.其中  $S_1$ 、 $S_2$  分别表示粗、细管的截面积,下标  $i, r, t$  分别代表入射、反射和透射波.

后面的  $S_2$  管对前面的  $S_1$  管来说是一个声负载,因而会引起部分声波的反射和透射.可以推得,平均声能流的透射系数为

$$t_w = \frac{I_t \cdot S_2}{I_i \cdot S_1} = \frac{4S_{21}}{(S_{21} + 1)^2} \quad (4)$$

其中  $S_{21} = S_1 / S_2$

平均声能流的反射系数为

$$r_w = \frac{I_r \cdot S_1}{I_i \cdot S_1} = r_p = \left[ \frac{S_{21} - 1}{S_{21} + 1} \right]^2 \quad (5)$$

分析式 (4)、(5) 可知,当  $S_{21} = 1$  时,即直管形式,  $t_w = 1, r_w = 0$ ,就是说平均声能流没有反射.当  $S_{21} > 1$  时,即为收缩管,  $1 > r_w > 0, t_w < 1$ ,就是说部分声能流反射回前段管内.由此可以看出,采用收缩管能有效地减少声能泄漏.

### 3.2 H600 H1000毫米里克-ZT型脉动燃烧器试验

燃烧室直径 H600 H1000毫米的脉动燃烧器结构尺寸见表 1,图 2是其结构示意图.

表 1 H600 H1000毫米里克-ZT型脉动燃烧器结构尺寸

	$d_1$ (mm)	$d_2$ (mm)	$d_3$ (mm)	$l_1$ (mm)	$l_2$ (mm)	$l_3$ (mm)	$l$ (mm)	$L/D$
H600 燃烧器	300	600	300	500	1850	300	650	4.42
H1000 燃烧器	450	1000	H150×	61000	2500	1000	1125	4.5

这两个脉动燃烧器采用两端收口的方法,成功地实现了长径比分别为 4.42、4.5的自然抽风自激脉动燃烧.实验中观察到,燃烧器工作非常稳定可靠,煤块燃烧完全,火焰猛烈,当煤层通风情况较好时出口处几乎看不到黑烟冒出.

图 3是 H600脉动燃烧器的频谱曲线.可以看出,管内传播的主要是频率为 33.62 Hz的基频波,高次谐波分量很少.由声级计测得燃烧器进口处声压为 83分贝(A声级);H1000脉动燃烧器的脉动频率为 22.5Hz,进口处声压为 78分贝(A声级).

实验中还发现,虽然两端收口以后燃烧器脉动

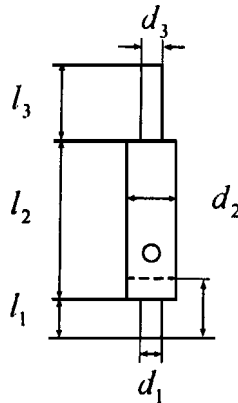


图 2 改进型里克脉动燃烧器

机理没有变化,但是其结构形状变了,长径比明显缩小了,工作频率不再满足  $1/2$ 波长管特性了,燃烧器的加热面位置也不同于直管形里克脉动燃烧器了.因此,将两端收口的改进型脉动燃烧器称为里克-ZT型脉动燃烧器.不难看出直管形里克脉动燃烧器是里克-ZT型脉动燃烧器的一种特殊形式.

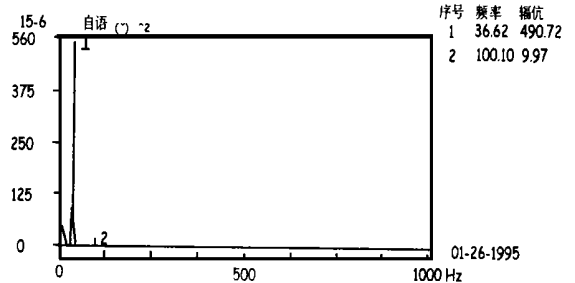


图 3 H600燃煤里克-ZT型燃烧器频谱分析

## 4 小 结

里克-ZT型脉动燃烧器利用两端收口增加声能反射的办法,成功地解决了小长径比里克型自激脉动的难题,且工作稳定.实验显示该型脉动燃烧器脉动机理没有大的改变,仍然是热声转换引起的自激驻波声学管共振,属于里克型脉动范畴.但其工作频率已不再满足  $1/2$ 波长管特性,与面积收缩比、收缩段的长度以及中间扩张段长度等因素都有关系.

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Yiqin // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 415~ 417

To fully utilize the low-temperature exergy of liquid hydrogen, installed additionally in a hydrogen energy-based gas turbine cycle is an air precooler and hydrogen turbine. Such a cycle enjoys a significant enhancement in specific power, thermal efficiency and exergy efficiency as compared with a simple cycle gas turbine. A thermodynamic analysis of the liquid hydrogen-gas power cycle is conducted and the latter's superior power performance predicted. Key words hydrogen energy-based gas turbine cycle, low-temperature exergy, thermal efficiency, analysis

管内复合强化传热技术及机理分析 = **In-tube Combination Intensified Heat Transfer Technology and An Analysis of its Mechanism** [刊, 中] / Gao Xiaotao ( Jiangsu Provincial Electric Power Test & Research Institute) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 418~ 420

With respect to in-tube intensified heat transfer and combination intensified heat transfer technology presented in this paper is an analysis of resistance and heat transfer characteristics under turbulent flow conditions. Experimental research results of several kinds of combination intensified heat transfer techniques are also given. It is pointed out that the insertion of a partial tube length twisted tape with a counter rotation in a spiral-corrugated tube can be regarded as a highly effective combination intensified heat transfer technique. Key words intensified heat transfer, combination intensified heat transfer, spiral-corrugated tube, twisted tape

碳钢-水热虹吸管内部强化传热机理研究 = **A Study of the Internal Intensified Heat transfer Mechanism of a Carbon Steel-Water Thermosyphon Pipe** [刊, 中] / Sun Shimei ( Jiling Chemical Engineering Institute) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 421~ 423

On the theoretical basis of a microlayer evaporation model an analysis is conducted of the intensified boiling heat transfer mechanism of thermosyphon pipe with an internally installed shunt tube structure. Set up is an internal boiling heat transfer model for a shunt tube intensified thermosyphon pipe. In addition, seven different kinds of perforated shunt tube structure have been selected for comparison with smooth tubes and for experimental study in order to seek an optimum shunt tube structure. A huge amount of experimental data is synthesized to establish a dimensionless number equation for intensified boiling heat transfer. Key words shunt tube, intensified boiling heat transfer, heat transfer model

煤颗粒流化床脱挥发份的实验研究 = **An Experimental Study of the Devolatilization of a Coal Particle Fluidized Bed** [刊, 中] / Zheng Shouzhong, Zeng Dong, Cai Song ( Southeastern University) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 424~ 426

A devolatilization test of coal particles was conducted on a small-sized fluidized bed test rig. Studied is the effect of bed layer temperature, coal type, ambient atmosphere and other factors on the changing behavior of such elements as C, H and N in the coal in the course of devolatilization. Key words coal fluidized bed, devolatilization

里克型脉动燃烧技术工程化应用实验研究 = **Experimental Research of Rijke Type Pulsating Combustion Technology and Its Engineering Applications** [刊, 中] / Zhong Yingjie, Chen Fulian, Shi Zhuling, et al (Zhe-

jiang Industrial University) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 427 ~ 428

The shortcomings of a straight tube Rijke type pulsating combustor are analysed. Through the use of contraction at two ends successfully realized is the coal pulsating combustion of a Rijke - ZT type pulsating combustor for a combustion chamber with a diameter of 1 meter and length-diameter ratio of 4.5. This leads to the preliminary resolution of the problem of creating a large-sized Rijke type pulsating combustor.

Key words pulsating combustion, Rijke type pulsating combustor, Rijke-ZT model pulsating combustor

煤焦特性及其  $N_2O$  生成影响因素的实验研究 = **An Experimental Study of Coal Char Properties and Its  $N_2O$  Generation Influencing Factors** [刊, 中] / Zeng Dong, Zheng Shouzhong, Cai Song (Southeastern University) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 429~ 431

The pyrolysis of two kinds of coal and coke combustion test has been conducted on a fluidized bed. Studied is the effect of coal type, particle diameter and pyrolysis conditions on coal char properties and  $N_2O$  conversion rate. The results of the study show that with the exception of the particle diameter both the coal type and pyrolysis conditions have a marked effect on  $N_2O$  conversion rate of N in the coal char. Key words coal char, nitrous oxide, pyrolysis, combustion

流化床锅炉床下点火装置的设计 = **The Design of an Ignition Device under a Fluidized Bed Boiler Bed** [刊, 中] / Yang Jialin, Chi Yong, Jiang Xuguang, et al (Zhejiang University) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 432~ 434

The superior advantages of an ignition mode under a fluidized bed boiler bed are listed. Presented are the design method and procedures of a pre-combustion cylindrical ignition device. In connection with practical applications some optimum design schemes have been proposed. Key words ignition device, fluidized bed, boiler start-up, burner, pre-combustion chamber

一种燃气轮机模块化非线性仿真模型 = **A Modularized Non-linear Simulation Model for Gas Turbines** [刊, 中] / Su Ming, Chen Delai, Zhang Yuanwei, et al (Shanghai Jiaotong University) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 435~ 437

Proposed is a method for setting up a gas turbine modularized simulation model based on typical components and segments or links. This method allows to avoid the iteration in differential equation right function calculation and simplify the simulation calculation flow process, thus enhancing the flexibility and universality of the model. Through tests and measurements it is found that the totally nonlinear simulation model set up with the help of the above-cited method can realize a realtime simulation on a 486 PC. Key words gas turbine, system simulation, modularized modeling

四边对流换热的内含热源各向同性矩形域稳态热传导解析 = **Anisotropic Rectangular Domain Steady-state Heat Conduction Analysis of Four-side Convection Heat Exchange in the Presence of an Internal Heat Source** [刊, 中] / Zhang Chengzong, Wang Anwen (Naval Academy of Engineering) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 438~ 440

Through an analytic solution of steady-state heat conduction of anisotropic rectangular domain in the pres-