

# 煤粉气流火焰稳定性条件分析\*

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[摘要] 试图通过简单的“输入—输出”关系,判别煤粉气流火焰稳定性。选择的“输入”参数为一次风工况初始条件,使判别准则直观合理。建立了回流区集总参数法热平衡模型,由此求解了保证火焰稳定的一次风煤粉浓度、风速、风温。并用单角煤粉炉热态实验的结果,对模型的可靠性进行了验证。

关键词 火焰稳定 判别准则 集总参数法模型

中图法分类号 TQ038

## 0 前言

研究火焰稳定性,涉及火焰稳定的定义和判据。由于煤粉燃烧过程中存在许多遵从唯象定律的不可逆过程,故难以对这一非平衡态热力现象抽象出一般热力学上的稳定性定义和判据。目前,关于煤粉火焰稳定的主要理论有:静态热平衡理论、搅拌均匀反应热理论,以及一些多维多相流动燃烧模型<sup>[1]</sup>。前两种理论基于零维或一维均匀热平衡模型,给定量分析带来不准确性,同时,一些研究者多考虑回流区长度和回流率的影响,并试图以此作为判据<sup>[2,3]</sup>。后一种方法实际上是数值模拟,考虑因素较全面,但计算工作量大,且不直观。

本文试图用简单“输入—输出”关系,判别火焰稳定性。“输入”参数为一次风工况条件:煤粉浓度、风速、初温;“输出”参数为回流区温度变化。整个建模与求解过程均结合燃烧器结构,这样,判别准则更为直观,且有针对性。

## 1 回流区热平衡模型

对钝体后流场作如下基本假设:

- (1)回流区是一个温度均匀的充分搅拌区;
- (2)回流区边界所进行的热质交换按雷诺比拟计算;
- (3)回流区中燃烧受挥发分燃烧控制。

通过回流区边界卷吸进回流区的煤粉( $I$ ),在回流区中停留时间定义为:回流区质量除以回流区与主流间的质量交换率<sup>[3]</sup>。即:

$$\tau_1 = \frac{V}{gs}$$

式中:  $V$ 为回流区体积,  $V = blh$ ;

$s$ 为回流区与主流热质交换面积,

$$s = 2lh;$$

$b$ 为钝体底边宽;

$h$ 为钝体高,即喷口高;

$l$ 为回流区长度;

$g$ 为主流与回流区质量交换系数,按 Spalding<sup>[4]</sup>给出的关系式:

$$g = \left(\frac{C_D}{4}\right) dU_0 \left(\frac{b}{l}\right) \quad (2)$$

相应热交换系数为:

$$T = \left(\frac{C_D}{4}\right) dC_P U_0 \left(\frac{b}{l}\right) \quad (3)$$

式中:  $C_D$  为钝体阻力系数;

$U_0$  为一次风速;

$d$  为气流密度;

$C_P$  为气流比热

为提高钝体稳燃能力,将钝体开中缝,使一股煤粉在回流区中首先着火,再点燃主流<sup>[5]</sup>。假设中缝气流遵从平面射流衰减规律:

$$\frac{U_x}{U_0} = C_j \left(\frac{b_1}{x}\right) \quad (4)$$

式中:  $b_1$  为开缝钝体中缝宽;

$C_j$  为衰减系数,实验得  $C_j = 4.2$

又,  $U_x = \frac{dx}{df}$  由此导出中缝流送入的煤粉

(II) 停留时间:

$$f_{II} = \frac{l^2}{2C_j U_0 b_1} \quad (5)$$

挥发分析出按  $F_v$ —Zhang 模型<sup>[6]</sup>计算:

$$\frac{dV}{df} = K(V' - V) \exp\left(-\frac{E}{RT}\right) \quad (6)$$

式中,  $V'$  为时间  $f \rightarrow \infty$  时,挥发分析出量;

$E$   $K$  为取决于环境温度的常数;

$R$  为气体常数;

将式(1)~(7)代入式(8)、(9),再根据式(10)可得:开缝钝体:

$$\geq \frac{C_P(T - T_0)}{HV' \left\{ 1 - \exp\left[-K \exp\left(-\frac{E}{RT}\right) \left(\frac{2l}{C_D U_0}\right)\right] \right\} + \left(\frac{2b_1}{C_D b}\right) \left\{ 1 - \exp\left(-\frac{E}{RT}\right) \left(\frac{l^2}{2C_j U_0 b_1}\right) \right\}} \quad (11)$$

钝体:

$$\geq \frac{C_P(T - T_0)}{HV' \left\{ 1 - \exp\left[-K \exp\left(-\frac{E}{RT}\right) \left(\frac{2l}{C_D U_0}\right)\right] \right\}} \quad (12)$$

对于正三角形钝体,  $C_D \approx 1.39, b_1/b = 0.1,$

$l/b = 5,$ 取:  $U_0 = 25 \text{ m/s}, T_0 = 350 \text{ K}, H =$

$70 \times 10^4 \text{ kJ/kg}, C_P = 1.3 \text{ kJ}/(\text{kg}^\circ\text{C}), E = 8.0$

$T$  为回流区温度

式(6)积分得:

$$V = V' \left\{ 1 - \exp\left[-K \exp\left(-\frac{E}{RT} f\right)\right] \right\} \quad (7)$$

建立热平衡关系式:

开缝钝体:

$$dC_P V \left(\frac{dT}{df}\right) = HC_g S V - TS \times (T - T_0) + HCU_0 b_1 h V d \quad (8)$$

钝体:

$$dC_P V \left(\frac{dT}{df}\right) = HC_g S V - TS(T - T_0) \quad (9)$$

式中:  $C$  为煤粉浓度;

$T_0$  为气流初温;

$H$  为单位质量挥发分的发热量

## 2 一次风工况与火焰稳定性关系

### 2.1 煤粉浓度的影响

由热着火理论,回流区火焰稳定须满足:

$$\frac{dT}{df} \geq 0 \quad (10)$$

$\times 10^4 \text{ kJ/mol}, K = 2.5 \times 10^4 \text{ 1/s},$ 可求得  $C_{min}-T$  关系曲线,如图 1

由图 1 可知,随  $V', T$  增大,  $C_{min}$  下降,当  $T$  较高时,即使低挥发分煤,也能在较低浓度下着火。

2.2 一次风风速的影响

同上理根据式 (10) 可求  $U_{max} - T$  关系, 迭代求解的结果见图 2

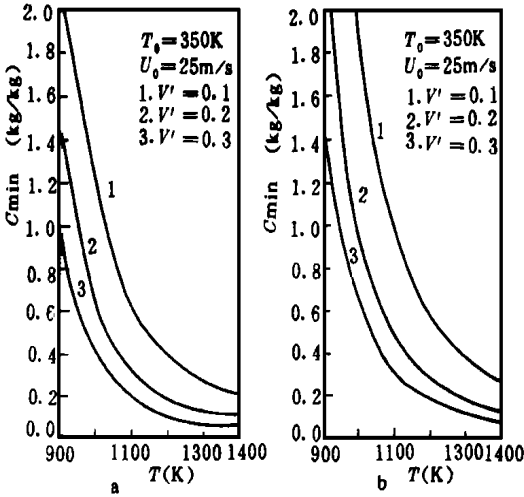


图 1  $C_{min} - T$  关系曲线  
a. 开缝钝体; b. 钝体

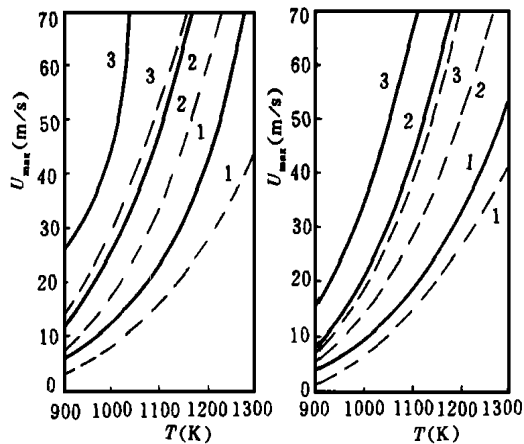


图 2  $U_{max} - T$  关系曲线  
— 开缝钝体 1.  $V' = 0.1$  2.  $V' = 0.2$  3.  $V' = 0.3$   
... 钝体  $C = 0.5 \text{ kg/kg}$  a.  $T_0 = 500 \text{ K}$  b.  $T_0 = 350 \text{ K}$

由图 2 可知, 随  $V'$ 、 $T$ 、 $T_0$  增大,  $U_{max}$  增大, 这时着火条件改善, 较大风速也难吹熄火焰。

2.3 一次风风温的影响

同上理推得  $T_0 - C$  关系, 求解结果如图 3 所示

由图 3 可知, 在  $V' = 0.1, C < 0.6 \text{ kg/kg}$  时,  $T_{0min} > 680 \text{ K}$  但实际工程中,  $T_0$  不可能这样高, 这说明, 在  $C < 0.6 \text{ kg/kg}$  时, 低挥发煤在  $T = 1000 \text{ K}$  时, 难以稳燃 只有增大  $T$  或  $C$ , 才能改善着火条件。当  $T = 1200 \text{ K}$  时,  $C \geq 0.3 \text{ kg/kg}$  就能保证火焰稳定了。

3 火焰稳定性实验

在单角煤粉炉上对上述以一维流为基础的模型进行验证, 实验煤种的工业分析见表 1, 其它实验条件详见文献<sup>[5,7]</sup>。

验证方法: (1) 将实验的的一次风工况参数 (除  $C_{实测}$  外) 代入式 (11)、(12), 分别求出开缝钝体和钝体的火焰稳定的最低煤粉浓度  $C_{min}$ ; (2) 将  $C_{min}$  与  $C_{实测}$  比较, 若  $C_{min} \leq C_{实测}$ , 则预测火焰可稳定; (3) 将预测结果与实验观察结果对照, 检验模型的可靠性 模型预测情况见表 2

表 1 实验用煤的工业分析

煤种	$C^y$ (%)	$V^y$ (%)	$W^y$ (%)	$A^y$ (%)	$Q_{dw}^y$ (kJ/kg)
劣质烟煤	32.78	11.19	8.08	47.95	14105
烟煤	43.86	21.69	2.16	32.31	21430
贫煤	63.14	11.20	3.65	22.01	26400
无烟煤	69.75	3.48	2.03	24.74	23300
混煤	66.45	7.34	2.84	23.37	24850

注 贫: 无烟 = 1:1

表 2 模型预测稳燃情况

(设  $T = 1300 \text{ K}$ )

煤种或来源	$V'$ (%)	开缝钝体		钝体	
		$C_{min}$ (kg/kg)	能否稳燃	$C_{min}$ (kg/kg)	能否稳燃
劣质烟煤	25.45	0.56	能	0.87	能
烟煤	33.07	0.43	能	0.67	能
贫煤	15.07	0.94	能	1.46	能
无烟煤	4.75	2.99	不能	4.63	不能
混煤	9.91	1.43	能	2.22	不能

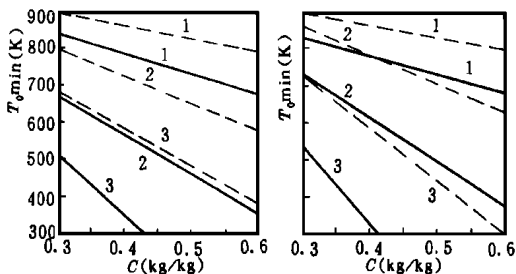


图 3  $T_{0min} - C$ 关系曲线

- 开缝钝体 a.  $U_0 = 25\text{ m/s}$ ,  $T = 1000\text{ K}$   
 1.  $V = 0.1$  2.  $V = 0.2$  3.  $V = 0.3$   
 b.  $U_0 = 25\text{ m/s}$ ,  $V' = 0.1$  1.  $T = 1000\text{ K}$   
 2.  $T = 1100\text{ K}$  3.  $T = 1200\text{ K}$

实验结果,当  $C_{\text{实测}} = 1.52\text{ kg/kg}$  时,对于开缝钝体,除无烟煤外,其它煤种均能稳燃,与模型预测一致;对于钝体只有烟煤、贫煤能稳燃;模型对劣质烟煤的预测与实验不符。这是因为近似取  $V' = V''$ ,而对于  $A^v = 47.9\%$  的劣质烟煤  $V'$  应与  $V''$  有较大差别。另外  $T = 1300\text{ K}$  取得较大,若取  $T = 1200\text{ K}$ ,则对劣质烟煤钝体燃烧器的预测也与实验一致。

#### 4 结束语

用一次风工况条件比用回流区长度、回流率作为火焰稳定性判据更为直观合理。通过开缝钝体和钝体回流区集总参数法热平衡

关系式,可近似地求得保证火焰稳定的最低煤粉浓度  $C_{\text{min}}$  最大一次风风速  $U_{\text{max}}$ ,最低初温  $T_{\text{omia}}$  模型预测的结果与实验基本一致

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(辉 编)

瑞典增压流化床联合循环发电技术的发展现状 = ( **The Present Status of Development of Swedish Power Generation Technology Involving the Use of a Pressurized Fluidized Bed Combined Cycle Unit** ) [刊, 中] / Li Daji ( Southeastern University ) // Journal of Engineering for Thermal Energy & Power. -1998, 13( 1). 1- 5

An on the spot survey of Swedish power generation technology involving the use of a pressurized fluidized bed combined cycle unit (PFBC-CC) was made in late April 1996 by a Chinese Delegation of Industrial Science & Technology. As a result, a comprehensive understanding has been gained of the research history and present status of the above-cited technology. This paper gives a brief description of the three types of PFBC plants of Swedish ABB Carbon Co. in respect of its preliminary test, intermediary test, commercial demonstration and application. **Key words** pressurized fluidized bed, combined cycle, Sweden, development

Stirling 发动机燃烧及换热分析 = ( **Analysis of a Stirling Engine Combustion and Heat Exchange** ) [刊, 中] / Shen Jianping, Jin Donghan, Gu Genxiang (No. 711 Research Institute under the China State Shipbuilding Corp. ) // Journal of Engineering for Thermal Energy & Power. -1998, 13(1). 6- 10

On the basis of a calculation of hydrocarbon fuel combustion chemical equilibrium reaction obtained are the temperature and component ingredients of the combustion products. Following this the combustion gas physical properties were calculated and based on this the convection heat exchange factor, radiation heat exchange factor and rear row heat exchange pipe rib heat transfer of a heat engine outer combustion system heating pipe were also calculated. A contrast computation is conducted of the two combustion conditions, air combustion and liquid oxygen combustion. Also computed are the various factors which have an influence on combustion with an analysis and discussion performed for the calculation results. The valuable conclusions obtained can serve as a guide for the structural design of the heat engine outer combustion system. **Key words** heat engine, heat exchange factor, combustion, chemical equilibrium

给水泵液力调速系统的特性及其非线性改善分析 = ( **Analysis of the Characteristics of a Feedwater Pump Hydraulic Speed Governing System and Its Non-linear Improvement** ) [刊, 中] / Wang Liwen ( China National Civil Aviation Institute ), Yan Guojun, Zhu Ruibin, Yang Huipu ( Harbin Institute of Technology ) // Journal of Engineering for Thermal Energy & Power. - 1998, 13( 1). - 11- 14

After an analysis of the regulating characteristics of the fluid coupling feedwater pump speed regulating system this paper gives a brief account of the principle of a variable function generator used for improving the serious nonlinearity of regulating characteristics and also the software and hardware design method. By way of an experimental analysis a scoop pipe-drive method is proposed for the improvement of a high-power variable speed fluid coupling. **Key words** variable speed fluid coupling, feedwater pump, nonlinearity

凝汽式汽轮机乏汽凝汽器强化的研究 = ( **A Study of the Exhaust Steam Condenser Heat Transfer Enhancement of a Condensing Steam Turbine** ) [刊, 中] / Lu Yingsheng, Zhuang Lixian, Deng Xianbe, Chen Guanghui, Chen Mulin ( South China University of Science & Technology ) // Journal of Engineering for Thermal Energy & Power. - 1998, 13( 1). - 15- 18

On the basis of an experimental study and analysis on the intensification mechanism of a high-efficiency heat transfer element (transversally corrugated tube) and its heat transfer and fluid mechanics conducted is the industrial application-oriented performance test of a 1500 kW condensing turbine condenser comprising glossy tubes and transversally corrugated tubes. The application prospects of the condensers made of transversally corrugated tubes are also given. **Key words** steam turbine, condenser, transversally corrugated tube, heat transfer intensification

煤粉气流火焰稳定性条件分析 = ( **Analysis of Pulverized Coal Current Flow Flame Stability Conditions** ) [刊, 中] / Ma Xiaoqian ( South China University of Science & Technology ), Jin Sijun, Si Xuefeng, Qian Ren-

zhang (Central China University of Science & Technology) // Journal of Engineering for Thermal Energy & Power. 01998, 13(1). - 19~ 22

Through a simple "input-output" relationship the ascertainment of pulverized coal flow flame stability is attempted. With the selected "input" parameter serving as the initial condition of a primary air operating regime the ascertainment criteria are made forthright and rational. A heat balance model based on the use of a return flow zone lumped parameter method has been established in order to solve for the primary air pulverized coal concentration, air speed and air temperature essential for the assurance of flame stability. The reliability of the model is verified by employing the hot-state experimental results of a single angle pulverized coal boiler. **Key words** flame stability, ascertainment criteria, model of lumped parameter method

几种常见锅炉事故的机理分析 = (An Analysis of the Underlying Causes for Several Kinds of Common Boiler Failures) [刊, 中] / Kuang Pingjian, Wu Qingyu, Gao Yukuan (Boiler & Pressure Vessel Inspection under the Harbin Municipal Labor Bureau) // Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 28~ 13

电站锅炉炉膛传热数值计算方法的研究 = (The Study of Furnace Heat Transfer Numerical Calculation Methods for Utility Boilers) [刊, 中] / Han Xiaohai, Zhang Mingchuan (Thermotechnical Institute under the Ministry of Electrical Power) // Journal of Engineering for Thermal Energy & Power, 1997, 12(6). - 23~ 27  
The present paper deals with a reactor network comprehensive model for the engineering use-oriented three-dimensional heat transfer numerical calculation of utility boiler furnaces. Prepared are three-dimensional comprehensive combustion-heat transfer process computational programs for pulverized-coal furnaces. Through the calculation of several different design and operating conditions the basic functions of the model are displayed and verified with some meaningful conclusions being obtained. **Key words** furnace heat transfer, mathematical model, pulverized coal combustion, reactor network

大型中温热管性能的试验研究 = (Experimental Study of the Performance of Large-sized Medium-temperature Heat Pipes) [刊, 中] / Yao Shouguang, Peng Dongsheng, Zhu Deshu (East China Shipbuilding Institute), Zhang Jianxun, Zhang Shuzhao, Mei Guozhong (Heat Pipe Research Institute of Jiangsu Xin Yuan Group Co.) // Journal of Engineering for Thermal Energy & Power, 1997, 12(6). - 32~ 36

Performance tests have been carried out with respect to some large-sized medium-temperature heat pipes filled with two kinds of new working mediums. On the basis of an analysis of the test data compared are the start-up and heat transfer characteristics of these two types of heat pipes. It has been found that in the medium-temperature range of 250~ 400°C there exists a marked difference in heat transfer performance between the heat pipes filled with these two different types of working mediums.

**Key Words** medium-temperature, heat pipe, performance

某大型综合补给船的自动电站系统 = (The Automated Power Station System of a Large-sized Comprehensive Replenishment Ship) [刊, 中] / Zheng Ziqian, Li Qiao (Harbin No. 703 Research Institute) // Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 37~ 39

This paper deals with the basic configuration and functions of an automated power station system for a large-sized comprehensive replenishment ship. **Key words** automated power station, replenishment ship

1021 t/h 煤粉锅炉高温炉管改造方案设计 = (Modification Design of High-temperature Boiler Flue Gas Tubes for a 1021 t/h Pulverized Coal-fired Boiler) [刊, 中] / Xing Changwen (Harbin No. 703 Research Institute) // Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 40~ 42

Based on the technical scheme design of high-temperature flue gas tubes of a 1021 t/h pulverized coal-fired utility boiler the author gives an analysis of the causes of the cited boiler tube failures during boiler operation.