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四角切圆煤粉锅炉燃烧工况评判方法研究

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摘　要：针对现有锅炉燃烧工况评判方法不足的实际情况，结合某 300 MW 四角切圆煤粉锅炉实炉运行工况，在确定各影响因素之间具有较强相关性后，用主成分分析法提取相关因子。再按各因子的方差贡献率加权相加并计算得分，用因子变量代替原有变量评价各影响因素作用的大小，依此得到的综合评价结果可正确反映锅炉的实际运行工况。与现有锅炉燃烧工况评判方法相比，避免了各因素之间不可比性给评判决策造成的困难。使应用此方法运行具有了明显的优越性。

关　键　词：四角切圆煤粉锅炉；燃烧评判；因子分析法；公共因子；方差贡献率

中图分类号：TK16；TK223.2　　文献标识码：A

引　言

电站煤粉锅炉的燃烧是一个复杂多变的过程。现有锅炉燃烧工况的评判主要是通过运行人员的经验结合锅炉燃烧调整试验结果等方法进行[1~4]。由于燃烧的影响因素众多，如锅炉负荷、燃料特性、一次、二次风速、二次风配风方式等，而各因素之间又有着非常复杂的关系，因此，锅炉燃烧状况的评判存在诸多不确定因素，其很难满足现场运行的要求。

本研究根据某 300 MW锅炉实炉工况，尝试利用因子分析法，对锅炉燃烧影响因素进行降维分析，从众多相关的影响因素中找出少数几个综合性的指标来反映锅炉运行所包含的全部信息，这样，运行人员能及时准确地对锅炉燃烧工况进行评判，更使锅炉燃烧的经济性、安全性和环保性指标都得到较好的优化。

1　因子分析法

因子分析是多元分析的一个分支，其基本目的是用少数几个随机变量描述许多变量之间的协方差关系。根据相关性大小把变量分组，使得同组内的变量之间相关性较高，但不同组的变量相关性较低。

因子分析的出发点是用较少的相互独立的因子变量代替原来数据的大部分信息，可以通过下面的数学模型来表示[5~8]：

$$x_1 = \alpha_{11}F_1 + \alpha_{12}F_2 + \cdots \alpha_{1m}F_m + C_1U_1 \quad (1)$$

$$x_p = \alpha_{p1}F_1 + \alpha_{p2}F_2 + \cdots + \alpha_{pm}F_m + C_pU_p \quad (2)$$

式中：F_j ($j=1, 2, \cdots, m$)出现于每个原观测变量的表达式中，是相互独立的不可观测的理论变量，称为公共因子，其含义根据具体的问题解释；U_i ($i=1, 2, \cdots, p$)是向量 X的分量 x_i ($i=1, 2, \cdots, p$)所特有的因子，仅与变量 x_i有关，称为特殊因子。系数 α_{ij}，C_i ($i=1, 2, \cdots, p$；$j=1, 2, \cdots, m$)称为因子载荷。

用矩阵可将式 (1)表示为：

$$X = AF + CU \quad (3)$$

式中：

$$A = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1m} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ \alpha_{p1} & \alpha_{p2} & \cdots & \alpha_{pm} \end{bmatrix}$$

$$C = \begin{bmatrix} C_1 & & & \\ & C_2 & & \\ & & 0 & \\ & & & C_p \end{bmatrix}$$

其中：A为因子载荷矩阵，A中的元素 α_{ij}为因子载荷。C_i^2称为变量 x_i的特殊因子方差。通过主因子能求出最具有影响力的公共因子。

2　基于因子分析法的煤粉锅炉燃烧工况评判

2.1　因子提取和分析

实际运行中，影响炉内燃烧的因素主要有锅炉负荷、总燃煤量、燃烧器摆角、一次风压、炉膛总风量、二次热风温度和一次热风温度等。利用 SPSS统

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计分析软件包对某 300 MW机组典型运行工况进行评判,具体参数如表 1所示。

利用 KMO(Kaiser-Meyer-Olkin)检验和巴特利特球形检验(Bartlett Test of Sphericity)来判断影响因素是否适合做因子分析[6]。锅炉燃烧工况影响因素的 KMO值为 0.731。根据 Kaiser的判别标准可知,所选影响因素能进行因子分析。锅炉燃烧工况影响因素的巴特利特球形检验值为 267.987,相应的概率值为 0.000,因此可以认为相关系数矩阵与单位阵有显著差异,即所选影响因素适合进行因子分析。

表 1　某 300 MW锅炉机组典型运行工况参数

	机组负荷 /MW	燃烧器摆角 /%	一次风压 / kPa	总煤量 / t· h^{-1}	炉膛总风量 / t· h^{-1}	二次热风温度 /℃	一次热风温度 /℃
1	322	31	10	122	1 217	337	76
2	318	32	10	134	1 298	337	67
3	316	40	10	139	1 227	342	73
4	314	32	10	131	1 210	334	87
5	312	45	10	140	1 225	334	73
6	312	32	10	139	1 233	338	72
7	308	34	10	139	1 293	337	74
8	298	30	11	145	1 220	338	70
9	287	33	10	132	1 238	335	71
10	279	33	10	120	1 033	333	84
11	278	36	10	121	1 209	332	71
12	264	30	10	118	1 107	333	70
13	262	32	10	111	1 131	339	72
14	260	30	10	101	985	332	70
15	247	35	10	105	1 085	333	69
16	227	67	10	98	982	333	75
17	226	45	10	102	971	327	78
18	213	29	10	95	868	322	74
19	212	31	10	86	813	321	70
20	206	31	10	85	807	319	78
21	192	51	10	82	833	321	68
22	188	39	10	89	794	319	85
23	173	43	10	80	777	321	72
24	171	41	10	69	718	323	79
25	169	37	10	72	779	322	72

表 2为因子表,由表可知,因子 1、因子 2和因子 3分别解释原有 10个变量的 50.06%、21.954%和 9.957%。3个因子共解释了原有变量总方差的 81.97%,反映了原有变量的大部分信息,因子分析效果比较理想。

图 1为公共因子碎石曲线。可见,第一个因子的特征值很高,对解释变量的贡献最大,第四个以后的因子特征值都较小,对解释原有变量的贡献很小,因此提取 3个因子是合适的。

表 3为因子负荷矩阵,根据该表可以写出锅炉燃烧影响因素的因子分析模型。

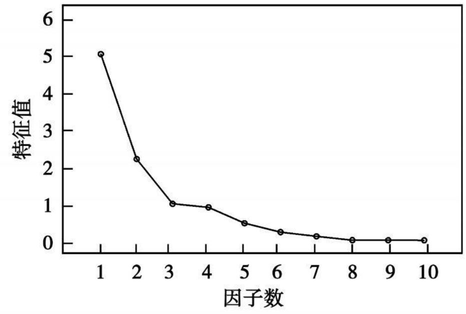

图 1　公共因子碎石

表 2 因子分析

因子编号	因子初始解			因子解			最终因子解		
	特征根值	方差贡献率/%	累积方差贡献率/%	特征根值	方差贡献率/%	累积方差贡献率/%	特征根值	方差贡献率/%	累积方差贡献率/%
1	5.006	50.060	50.060	5.006	50.060	50.060	4.370	43.702	43.702
2	2.195	21.954	72.014	2.195	21.954	72.014	2.790	27.904	71.605
3	0.996	9.957	81.970	0.996	9.957	81.970	1.037	10.365	81.970
4	0.902	9.019	90.990	—	—	—	—	—	—
5	0.475	4.752	95.742	—	—	—	—	—	—
6	0.236	2.365	98.107	—	—	—	—	—	—
7	0.125	1.247	99.354	—	—	—	—	—	—
8	0.024	0.240	99.594	—	—	—	—	—	—
9	0.022	0.225	99.819	—	—	—	—	—	—
10	0.018	0.181	100.000	—	—	—	—	—	—

表 3 因子负荷矩阵

	因子		
	1	2	3
锅炉负荷	0.895	−0.366	0.094
燃烧器摆角	−0.263	0.339	0.192
一次风压	0.778	−0.112	−0.012
总煤量	0.926	−0.299	0.095
炉膛总风量	0.920	−0.325	0.003
二次热风温度	0.902	−0.225	0.015
一次热风温度	−0.215	−0.083	0.950
飞灰可燃物含量	0.511	0.805	−0.040
炉膛壁面热负荷	0.609	0.755	−0.024
炉膛出口 NO_x含量	0.580	0.680	0.190

由表 3可知，除燃烧器摆角外，燃烧工况影响因素变量在第一个因子上的负荷都比较高，意味着它们与第一个因子的相关程度高，其余两个因子与各变量的相关性较小。

用主成分分析法进行方差极大法旋转后，在公共因子 F_1 上占有较大载荷的是锅炉负荷（0.967）、一次风压（0.736）、总煤量（0.963）、炉膛总风量（0.963）、二次热风温度（0.901），这 5个变量都与锅炉燃烧工况有直接关系，定义 F_1 为燃烧因子。在公共因子 F_2 上占有较大载荷的炉膛出口处飞灰可燃物含量（0.945）、炉膛壁面热负荷（0.947）、炉膛出口 NO_x含量（0.883），这 3个变量均与燃烧状况好坏的评价有关，定义 F_2 为燃烧工况评价因子。在公共因子 F_3 上占有较大载荷的是燃烧器摆角（0.206）和一次热风温度（0.969），这两个变量与燃料的着火有关系，定义 F_3 为着火因子。

2.2 锅炉燃烧工况的评判

利用公共因子，并按其各自的方差贡献率加权相加计算综合评价得分，评价各因素影响作用的大小，避免了各因素之间不可比性给评判决策造成的困难，使综合评判的结果正确反映了客观实际，其计算为：

$$F=0.50F_1+0.22F_2+0.10F_3 \quad (4)$$

由综合评价得分的大小确定某一燃烧工况的好坏，如表 4所示。

表 4 燃烧工况评价结果

工况	机组负荷/MW	燃烧器摆角/%	一次风压/kPa	总煤量/t·h⁻¹	炉膛总风量/t·h⁻¹	二次热风温度/℃	一次热风温度/℃	壁面热负荷/W·m⁻²	飞灰含碳量/%	NO_x含量/mg·m⁻³	F	评价结果
1	320	31	10	122	1 217	337	76	489 558.0	5.00	682.00	0.498 49	较好
2	320	32	10	134	1 298	337	67	505 407.0	5.17	693.00	0.520 81	一般
3	320	40	10	139	1 227	342	73	542 388.0	5.54	700.00	0.758 98	较差

由上述分析可以得到最优燃烧工况，以锅炉高负荷运行为例，当锅炉负荷为 320 MW时，工况 3的燃烧工况较差，工况 3相对于工况 1而言，燃烧器向上摆角为 40%，这就造成火焰中心上移，飞灰可燃

物含量为 5.54%, 大于工况 1的 5.00。同时燃煤量为 139 t/h, 炉膛出口处 NO_x含量为 700.00 mg/m³, 均大于工况 1, 所以锅炉运行的经济性、环保性、安全性均不如工况 1。工况 2介于二者之间, 由此可以得出锅炉负荷在 320 MW时, 推荐最优运行工况应该为工况 1。

3 结　论

(1)定义了 F_1 为燃烧因子, F_2 为燃烧工况评价因子, F_3 为着火因子。用因子变量代替原有变量, 将 10个燃烧工况影响因子缩减为 3个主因子作为评判依据, 实现了降维和简化的目的。

(2)利用公共因子按各自的方差贡献率加权相加, 并计算综合评价得分, 进而确定燃烧工况的优劣, 得出锅炉负荷在 320 MW时, 推荐最优运行工况为工况 1, 此时飞灰可燃物含量为 5%, NO_x含量为 682 mg/m³, 均优于其它比较工况。

(3)采用因子分析法, 结合锅炉实炉运行情况, 对锅炉燃烧工况进行评判。综合评判的结果正确反映了锅炉实际运行工况, 相对现有锅炉燃烧工况其它评判方法, 具有一定的优越性, 对电厂优化燃烧, 具有指导意义。

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(编辑　陈　滨)

新技术、新工艺

燃气涡轮第一级静叶空气的对流和气膜冷却

《Теплоэнергетика》2009年 7月号提供了关于具有对流气膜冷却的第一级静叶全套计算方法的制定、冷却叶片的流体特性、热力特性和强度特性的信息。

根据计算结果, 做出了有关燃气主流对冷却剂喷流有明显影响的结论。

利用全套程序 ANSYS确定叶片的受力形变状态, 允许根据热力计算结果自动地确定叶片横截面内最危险的点并允许根据总应力计算持久静强度安全系数; 允许根据低循环等温疲劳曲线估算容许的循环数。

根据所完成的研究, 制定并试验论证了用于 60 MW功率的发电用燃气轮机装置涡轮第一级静叶的空气对流气膜冷却系统。

利用全套程序 COLD和商用软件包 FLUENT制定了高温燃气涡轮(涡轮前燃气初温为 1 427 ℃)具有对流气膜冷却的第一级静叶热力计算的综合方法。

根据被试验的冷却静叶热力和流体试验的试验数据, 检验并修正了所制定的方法。

(吉桂明　摘译)

136300)// Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —399~401

A combustion test was performed of a gas production slag and anthracite mixed fuel by using a high temperature trace thermal scale. TG (thermogravimetric) and DTG (derivative thermogravimetric) curves at different mixing ratios of the gas production slag and anthracite were obtained and the influence of different mixing ratios on the mixed combustion of the gas production slag and anthracite was analyzed with the ignition temperatures and combustion characteristic indexes of the combustion of the mixed fuel being acquired. The research results show that the combustion characteristic indexes of the mixed combustion of the mixed fuel will first decrease, then increase and finally decrease with an increase of the slag-coal ratio. When the slag/coal ratio is 4∶6, the combustion characteristic index will reach its maximal value. When the slag/coal ratio is 5∶5, the combustion characteristic index will be only inferior to that of the slag/coal ratio being 4∶6. When the slag and coal are not mixed and diluted, the combustion characteristic index will be very small. When the slag and coal are mixed and diluted, the combustion characteristic index will be much greater. Key words: coal-gas production slag, thermogravimetric analysis, combustion, loss-on-ignition

对火电厂循环冷却水浓缩倍率的分析研究 = Analysis and Study of the Concentration Rate of the Circulating Cooling Water in a Thermal Power Plant[刊, 汉] / WANG Rong, SHEN Bing-yun, LIU Wen-chao (College of Energy Source and Power Engineering, Inner Mongolia Polytechnic University, Huhhot, China, Post Code: 010051)// Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —402~405

When the circulating cooling water system of a thermal power plant in Inner Mongolia was in actual operation, its concentration rate would be only 1.9. As a result, a chemical agent replacement test was performed. When a chemical agent sifting test was being performed, a static simulation test was first performed of two kinds of chemical agent. It has been determined that when the dosages of the two chemical agents are 10 mg/L, the fouling resistance effectiveness will attain its best. Through a dynamic simulation test, it has been verified that the fouling-resistance etching-retarding performance of JD~211A chemical agent is superior to that of JD~211B chemical agent. When no acid is added, the safe concentration rate can reach 2.5. Therefore, to use JD~211A chemical agent can save a large amount of makeup water. Finally, the cost effectiveness by replacing the chemical agent was calculated. It has been verified that to enhance the concentration rate can bring about an economic benefit of more than RMB 1.24 million yuan each year to an enterprise. Key words: circulating and cooling water, concentration rate, steam condenser

四角切圆煤粉锅炉燃烧工况评判方法研究 = Study of Methods for Evaluating and Judging the Combustion Conditions of a Tangentially Corner-fired Boiler[刊, 汉] / LI Jun, YAN Wei-ping (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control, North China University of Electric Power, Baoding, China, Post Code: 071003), LI Chun (Dispatchment Station, Xinzhou Power Supply Company, Xinzhou, China, Post Code: 036000)// Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —406~409

In the light of the actual situation that the currently available methods for evaluating and judging the combustion conditions of a boiler are insufficient and in combination with the actual operating conditions of a 300 MW tangentially corner-fired pulverized coal boiler, a main component analytic method was used to extract correlative factors after a relatively strong correlation has been confirmed being present among various influencing factors. Subsequently, the factors were weighted as per their mean square deviation contribution rates and added up to calculate the scores. Factor variables were used to replace the original variables for evaluating the magnitudes of the roles played by various influencing factors. The comprehensive evaluation results thus obtained can correctly reflect the actual operating conditions of the boiler. Compared with the currently available methods for evaluating and judging the combustion conditions of a boiler, the abovementioned method can avoid the difficulty for evaluation, judgement and policy-making caused by the incomparability of various factors, making the operation realized by using the method in question enjoy a conspicuous superiority. Key words: tangentially corner-fired pulverized coal boiler, combustion judgement, factor analytic method, common factor, mean square deviation contribution rate

混煤可磨特性与掺烧方式试验研究 = Experimental Study of the Grindability and Mixed-diluted Combustion Mode of a Blended Coal[刊,汉] / DUAN Xue-nong, ZHU Guang-ming, JIAO Qing-feng (Experiment Research Institute, Hunan Provincial Electric Power Corporation, Changsha, China, Post Code: 410007), YAO Bin (College of Energy Source and Power Engineering, Central China University of Science and Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —410 ~ 413

Experimentally studied were the grindability and the variation law of the particle diameter distribution of four kinds of typical lean coal and anthracite respectively in different coal mixing modes in a laboratory. The test results show that the grindability of the blended coal tends to be such as assumed by coal ranks diffifult to grind, i. e. in the pulverized coal samples, the coarse particles pertain to more-difficult-to-grind coals while the fine particles involve more easily grindable coal ranks. The test results were explained physically from the angle of the standard testing of grindability. It has been concluded that the grindability of a blended coal must be determined through tests. The pulverized coal fineness of a blended coal must be decided by a coal rank with a relatively low volatile content when it is "mixed and diluted in front of the furnace" and a rational fineness for each coal component must be chosen when separate milling is adopted. For the mixed/diluted combustion of coal ranks with a relatively big difference in grindability, an optimization test was performed of three "separate milling" mixed/diluted combustion modes in the light of specific features of the milling and combustion system. By controlling relatively well the pulverized coal finenesses of difficult-to-grind and difficult-to-burn-out coal ranks, the boiler efficiencies were invariably enhanced by more than 1.5% when compared with that in the traditional "mixing/dilution in front of the furnace" combustion mode. Key words: blended coal, grandability, particle diameter distribution, burn-out characteristics, separate milling

基于遗传算法的 PID参数整定在高温多相流风洞中的应用 = Application of PID (Proportional, Integral and Differential) Parameter Setting Based on a Genetic Algorithm in a High-temperature Multiphase Flow Wind Tunnel[刊,汉] / XU Ting-yan, PU Xing-guo, YUAN Zhen-fu (National Key Laboratory on Clean Utilization of Energy Source, Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(4). —414 ~417

A high-temperature multiphase flow wind tunnel can simulate gas-solid two-phase flow conditions during the operation of a boiler, facilitating the study of flow characteristics and testing methods. To better control the technical parameters of the wind tunnel, PID (proportional, integral and differential) controllers were adopted in the main control loops of the wind tunnel and the PID parameters were set based on a genetic algorithm. The choice of the target function based on the genetic algorithm and the concrete operations of the genetic algorithm were described in detail with the option operations being coupled with optimum preservation tactics. By using software Matlab, a simulation was performed of the PID parameter setting of temperature control objects based on the genetic algorithm. The set PID parameters were used for on-site commissioning test, and $k_p = 0.2173$, $k_i = 0.4505$ and $k_d = 0.0758$ were obtained after a tiny correction. During the test, the maximal dynamic deviation of temperature was 1 ℃, thus attaining a good control quality. Key words: genetic algorithm, PID (proportional, integral and differential), parameter setting, wind tunnel, high-temperature multiphase flow