文章编号: 1001 - 2060(2011) 01 - 0097 - 03

基于最小二乘支持向量机的煤粉着火温度预测分析

常爱英, 吴铁军, 赵　虹, 包　鑫
(浙江大学 工业控制技术国家重点实验室, 浙江 杭州 310027)

摘　要: 针对关系到锅炉经济安全运行的煤着火温度估计难的问题, 采用最小二乘支持向量机方法建立煤粉着火温度的预测模型, 并和利用 PLS 以及 BP 神经网络等方法建立的预测模型进行对比, 结果表明, 最小二乘支持向量机克服了 BP 神经网络泛化能力弱以及 PLS 无法解决的非线性等问题, 采用最小二乘支持向量机方法建立的煤粉着火温度模型具有很高的预测精度。

关　键　词: 煤粉; 着火温度; 预测模型; 最小二乘支持向量机; BP 神经网络; PLS

中图分类号: TQ533　　**文献标识码**: A

引　言

目前, 电厂基本以挥发分、热量、灰分为主要指标判断煤着火特性, 这往往会出现较大偏差。实验室研究主要是利用沉降炉、一维炉、热天平等测量煤粉着火温度, 通过单变量回归分析建立着火温度指数[1~3], 由于煤着火温度指数和煤质分析是复杂的非线性关系, 所以预测精度差。很多学者采用 BP 神经网络建立煤粉着火指数的模型[4~5], 3 层 BP 神经网络可以拟合任何连续函数, 但泛化能力很差。支持向量机(Support Vector Machine, SVM) 基于结构风险最小化的原则考虑学习机器的推广能力, 最小化推广误差的上界, 有较好的泛化性能。最小二乘支持向量机(Least Squares Support Vector Machines, LSSVM) 作为 SVM 的一种改进技术, 使计算速度提高, 已在很多领域得到广泛应用[6~8]。

本研究采用 LSSVM 方法建立煤着火温度预测模型, 并与 BP 神经网络、PLS 线性回归方法建立的煤着火温度预测模型的效果进行对比, 用以明确最小二乘支持向量机法的预测能力, 以期为电厂实际运行提供参考。

1　最小二乘支持向量机原理

LSSVM 用于回归的原理为[9~11]: 给定一个有 N 个样本数据组成的训练集$\{x_k, y_k\}_{k=1}^{N}$, 输入数据 $x_k \in R^m$, 输出数据 $y_k \in R$, 函数拟合问题可以描述为以下最优化问题:

$$\min j(w, e) = \frac{1}{2} w^{\mathrm{T}} w + \frac{1}{2} \mathrm{Gama} \sum_{k=1}^{N} e_k^2 \qquad (1)$$

$$y_k = w^{\mathrm{T}} \varphi(x_k) + b + e_k, k = 1, \cdots, N$$

式中: $\varphi(\cdot): R^m \rightarrow R^{m_h}$ 用于将输入数据从空间 R^m 映射到高维特征空间 R^{m_h}; $w \in R^{mk}$ 为加权向量; Gama > 0 为惩罚系数, 可以调整误差所起的作用; $e_k \in R$ 为误差变量, $b \in R$ 为偏置值。

式(1) 的最优化问题可变换到对偶空间加以求解, 得 LSSVM 拟合模型为:

$$y(x) = \sum_{k=1}^{N} \alpha_k K(x_k, x) + b \qquad (2)$$

式中: α_k—支持向量, α_k 和 b 可根据训练样本数据求得; $K(x_i, x_j)$ —核函数, 选择比较常用的高斯函数为核函数:

$$K(x_i, x_j) = \exp(-\| x_j - x_i \|^2 / \mathrm{Sigma}) \qquad (3)$$

2　煤粉燃烧实验

2.1　煤质分析

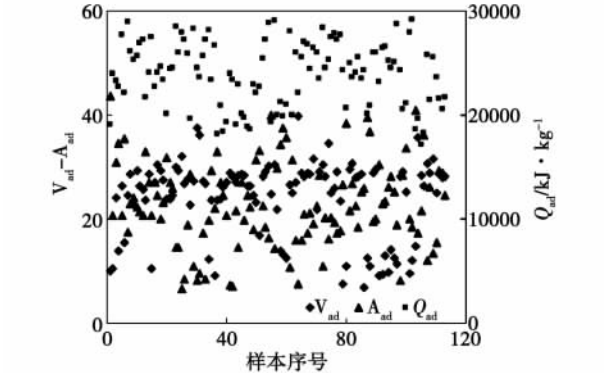

图 1　主要煤质分析分布

收稿日期: 2010 - 01 - 07;　**修订日期**: 2010 - 04 - 23
作者简介: 常爱英(1975 -) , 女, 吉林白城人, 浙江大学博士研究生.

所有煤样均来自某省份电厂实际燃用煤种，涵盖了褐煤、烟煤、劣质烟煤、贫煤、无烟煤等，空气干燥基发热量为 17 178 ~ 29 257.2 kJ/kg、挥发分含量为 6.73% ~ 39.8%，样品主要煤质分析如图 1 所示。

2.2 煤粉着火温度的确定

利用德国 Netzsch 公司产的 NETZSCH STA 449C 型热天平完成煤粉热失重实验，用热天平进行煤粉燃烧实验，具有实验重现性好，测量精度高的优点，是目前研究煤粉着火特性的主要研究方法。工作气氛模拟空气，N_2 和 O_2 的流量分别为 80 和 20 mL/min，升温速率为 20 ℃/min，样品重量为 10 mg。采用比较通用的切线法确定着火温度[4]，实验得到煤样着火温度如表 1 所示。

表 1 煤粉着火温度分布

序号	着火温度/℃	序号	着火温度/℃	序号	着火温度/℃
1	452	39	436.5	77	413.9
2	451	40	412.7	78	423.9
3	418.2	41	372.2	79	481.2
4	438.1	42	378.5	80	446.7
5	411.3	43	414.6	81	409.6
6	437.3	44	394.9	82	414.7
7	423.7	45	413.9	83	410.6
8	415.4	46	413.8	84	420.4
9	440.4	47	406.5	85	420.4
10	414.8	48	409.6	86	483.2
11	424.6	49	421.6	87	451
12	425.5	50	425.7	88	462.3
13	428.9	51	427.1	89	415.4
14	413.9	52	417.2	90	419
15	451	53	413.2	91	463.9
16	418.9	54	417.5	92	459.5
17	412.3	55	401.1	93	449.6
18	411.5	56	414.4	94	456.5
19	411.5	57	442	95	450.5
20	429.6	58	431.5	96	457.7
21	425.5	59	436.6	97	446.5
22	437.7	60	441.7	98	361.2
23	402.5	61	420.7	99	418.8
24	389.4	62	411.1	100	413.8
25	371.9	63	408.5	101	468
26	400.6	64	321.5	102	446.5
27	418	65	407.8	103	442
28	446.4	66	419.5	104	334.1
29	420.7	67	410	105	352.4
30	354.6	68	396.4	106	398.5

续表 1 煤粉着火温度分布

序号	着火温度/℃	序号	着火温度/℃	序号	着火温度/℃
31	355.8	69	400.9	107	367.1
32	399.6	70	429.9	108	411
33	400.6	71	411.6	109	389.8
34	439.5	72	402.5	110	363.5
35	440.3	73	397.7	111	335.8
36	452.1	74	373.5	112	336.8
37	428.9	75	412.2	113	406.2
38	421.2	76	416		

3 煤粉着火温度的预测模型

3.1 数据预处理与模型参数的选取

利用 LSSVM 预测煤粉着火温度，样本集 $\{x_k, y_k\}_{k=1}^{N}$ 的输入变量 $x_k \in R^m$，取煤工业分析的挥发分、水分、固定碳、发热量以及元素分析中的碳、氢、氧等对煤着火特性有影响的参数[12]；输出变量 $y_k \in R$ 为煤着火温度指数。样本进行标准化预处理：

$$x'_{ik} = \frac{(x_{ik} - \bar{x}_i)}{S_i} \tag{4}$$

式中：x'_{ik}—标准化后的第 k 个样本的第 i 个变量；x_{ik}—第 k 个样本的第 i 个变量；$\bar{x}_i$—第 i 个变量的均值；S_i—第 i 个变量的标准差。

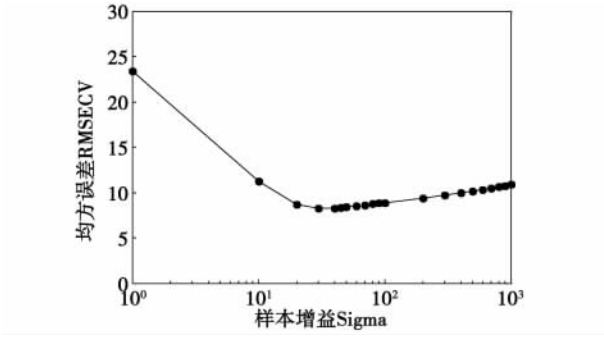

图 2 Sigma 对 RMSECV 的影响

利用 LSSVM 建立煤粉着火温度的预测模型，需要确定的参数包括样本增益 Sigma 和支持向量机的罚函数系数 Gama。本研究采用留一交叉验证法确定最优参数，即依次剔除一个样本后用剩余的样本建模，再用模型预测剔除样本的着火温度指数，评价指标为均方误差(RMSECV)。

实验涉及到的算法程序均由 Matlab 7.1 编写，在 Core 2 微机 Windows XP 环境下运行。首先固定 Gama 为 10，计算不同 Sigma 值样本的预测均方误差，仿

真结果如图 2 所示,取预测均方误差最小值对应的 Sigma 值为最优值,参数 Sigma 的最优值为 60。按照确定 Sigma 最优值的方法确定参数 Gama 的最优值,仿真结果如图 3 所示,参数 Gama 的最优值为 120。

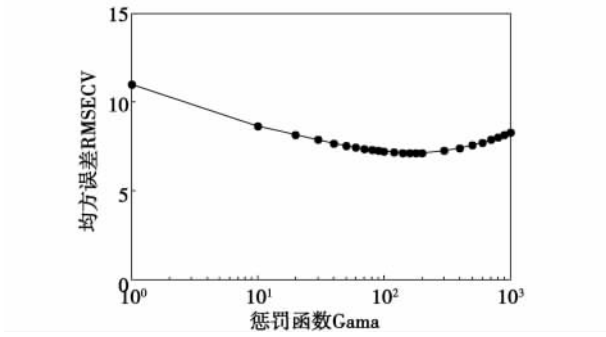

图 3　Gama 对 RMSECV 的影响

3.2　预测效果的对比

将样本随机抽取 10% 作为测试集,剩余作为训练集用于建立模型。为了明确 LSSVM 建立煤粉着火温度模型的预测能力,采用 LSSVM 和 PLS 方法以及 BP 神经网络分别建立煤粉着火温度的预测模型,采用留一法交叉验证的方式,通过误差均值,均方误差,相对误差,相关系数等评价参数比较各种方法预测性能的优劣。其中,LSSVM 的参数值 Gama 为 120,Sigma 为 60。BP 神经网络采用文献[5]中的参数,2 个隐含层,神经元个数分别为 14,22,激活函数为 tansig,logsig。

仿真计算得到各评价参数如表 2 所示。

表 2　几种预测方法的对比

方法	误差均值	均方误差	相对误差/%	相关系数
LSSVM	-0.16	7.15	0.17	0.95
BP	-1.71	17.25	0.50	0.63
PLS	-0.01	10.26	0.25	0.87

由于煤粉的工业分析、元素分析和着火温度指数的非线性关系,导致利用 PLS 线性方法进行着火温度预测的均方误差、相对误差、相关系数等参数明显劣于 LSSVM 方法。由于神经网络基于经验风险最小化原则基础上实现的,过学习问题导致模型的泛化能力较差,均方误差为 17.25,高于 LSSVM 的 7.15,相关系数是 0.63,相对 LSSVM 的 0.95 低很多。可见,使用 LSSVM 方法预测煤粉着火温度是可行的。

3.3　预测模型

测试集样本着火温度的预测值和实验值如图 4 所示,预测值均方误差为 6.80,相对误差为 0.48%,相关系数为 0.95。

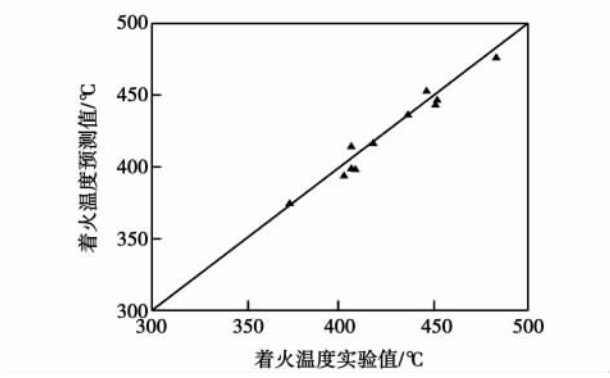

图 4　测试集样本煤粉着火温度

4　结　论

本研究分别用 LSSVM、BP 神经网络和 PLS 方法建立煤粉着火温度预测模型并比较预测结果,研究表明: LSSVM 算法通过最小化置信范围和最小化经验风险,克服了过学习导致泛化能力弱问题,LSSVM 方法的预测效果远远好于 BP 神经网络、PLS 线性回归方法,有较高的预测精度,可以应用到实际电厂运行指导中。

参考文献:

[1] 傅维标,张恩仲. 煤焦非均相着火温度与煤种的通用关系及判别指标[J]. 动力工程,1993,13(3):15-18.
[2] 朱　跃,郭文靖. 煤的热天平分析试验结果与工业分析数据的相关性研究[J]. 黑龙江电力技术,1998(10).257-263.
[3] 朱群益. 煤粉着火温度与煤的元素分析及工业分析的关系[J]. 哈尔滨工业大学学报,1993,25(2):25-28.
[4] 周　坤,杨建国. BP 神经网络对煤着火特性的预测[J]. 热力发电,2005,34(11):21-25.
[5] 杨建国. 采用遗传算法优化的煤粉着火特性 BP 神经网络预测模型[J]. 动力工程,2006,26(1):81-83.
[6] CHEN Q,ZHAO J,FANG C H,et al. Feasibility study on identification of green, black and Oolong teas using near-infrared reflectance spectroscopy based on support vector machine[J]. Spectrochimica Acta, 2007,66(3):568-574.
[7] 吴德会. 基于 LS-SVM 的特征提取及在凝点软测量中的应用[J]. 系统仿真报,2008,20(4):917-920.
[8] BORIN A, FERRÃO M F,MELLO C,et al. Least-squares support vector machines and near infrared spectroscopy for quantification of common adulterants in powdered milk[J]. Analytica Chimica Acta, 2006, 579:25-32.
[9] VAPNIK V N. Statistical learning theory[M]. New York: John Wiley,1998.
[10] SUYKENS J A K,VANDEWALLE J. Least squares support vector machine classifiers[J]. Neural Processing Letters, 1999,9(3): 293-300.
[11] 边肇祺,张学工. 模式识别[M]. 北京: 清华大学出版社,2000.
[12] 朱群益,赵广播. 煤粉着火温度与煤的元素分析及工业分析间的关系[J]. 哈尔滨工业大学学报,1993,25(2): 25-28.

89 ~ 93

With the help of CFD (computational fluid dynamics) software Fluent and by choosing a rational mathematical model, a numerical simulation was performed of a 600 MW ultra-supercritical wall-type-arranged tangentially-fired boiler. The influence of the aerodynamic field, temperature field, component field and different SOFA (separated over-fired air) air ratios on the NO_x generation and flue gas constituent characteristics of the boiler in question were mainly studied. The research results show that the in-furnace tangential circle is completely formed with a relatively good filling degree, but the tangential circle being formed is excessively large, the temperature nearing the wall surfaces is unduly high and the slagging tendency is conspicuous. Such a conclusion is in good agreement with that obtained from the fog tracer test performed on a test stand, having proved that the simulation is reliable. With an increase of the SOFA air ratio, the oxygen concentration in the main combustion zone will decrease and NO_x produced in the main combustion zone will also diminish. Under the condition of the SOFA air ratio being excessively high, the NO_x produced in the later-stage combustion will increase greatly and the NO_x emissions will not be necessarily low as a whole. Therefore, it will be necessary to rationally optimize the SOFA air ratio. **Key words**: wall type tangentially-fired boiler, NO_x, SOFA (separated over-fired air) air ratio

船用增压锅炉热平衡及热损失的计算方法 = **Method for Calculating the Heat Balance and Thermal Loss of a Marine Turbocharged Boiler** [刊, 汉] WANG Yong-tang, WU Shao-hua (College of Energy Science and Power Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001), CHEN Ming, WANG Jian-zhi (CSIC Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). - 94 ~ 96

Heat balance calculation is crucial for calculating the thermodynamic performance of a marine turbo-charged boiler. By performing an analysis and explanation in the light of the structural and operation features of a turbocharged boiler with its turbocharged unit doing work, the authors have proposed a method for calculating the heat balance and thermal loss of a marine turbocharged boiler with the heat absorbed by the air interlayer being taken into account, presented a formula for calculating the heat entered into the furnace and various losses, especially the thermal loss and heat isolation coefficient of the turbocharged unit and performed a thermodynamic check calculation of the turbocharged boiler with or without the influence of the air interlayer. The calculated results approximate to the actual conditions. The calculation method being proposed by the authors can provide reference for thermodynamic performance calculation of marine turbocharged boilers. **Key words**: marine turbocharged boiler, heat balance, air interlayer, heat dominated, heat dissipation loss

基于最小二乘支持向量机的煤粉着火温度预测分析 = **Prediction and Analysis of Pulverized Coal Ignition Temperature Based on a Least Square Supportive Vector Machine** [刊, 汉] CHANG Ai-ying, WU Tie-jun, ZHAO Hong, et al (National Key Laboratory on Industrial Control Technology, Zhejiang University, Hangzhou, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). - 97 ~ 99

In the light of the problem relating to the economic and safe operation of a boiler that it is difficult to predict the ig-

nition temperature of coal, the least square supportive vector machine method was used to establish a model for predicting the ignition temperature of the coal and compare it with the prediction models established by using the PLS (partial least square) and BP (back propagation) neural network method etc. The research results show that the least square supportive vector machine can overcome the problems such as weak generalization ability of the BP neural network and nonlinearity that the PLS method has no way to solve. The model under discussion enjoys a very high prediction precision. **Key words**: pulverized coal, ignition temperature, least square supportive vector machine, BP (back propagation) neural network, partial least square (PLS)

煤拔头烟煤焦的物质组成及碳结构 = **Substance Composition and Carbon Structure of Coal-topping Bituminous-coal Coke** [刊,汉] SHEN Chun-mei, WU Shao-hua (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001), LIN Wei-gang, SONG Wen-li (Process Engineering Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). - 100 ~ 104

With Da-tong originated bituminous coal in three particle diameters (DT60, DT80 and DT100) serving as the raw material, the coal-topping semi-cokes at four pyrolysis temperatures (550, 650, 750 and 850 ℃) were prepared respectively on a spouted-entrained bed. The industrial analytic, infrared spectrum analytic and X-ray diffraction analytic methods were used to test the substance composition and carbon structure of the coal-topping semi-cokes. It has been found that the substance composition and carbon structure of the coal-topping semi-cokes are related to its raw coal hypolysis degree (D_V), which will increase with an increase of the hypolysis temperature, temperature rise speed and residence time. The order of D_V magnitudes of raw coal in different particle diameters at a same pyrolysis temperature is basically as follows: $D_{V,DT60} > D_{V,DT100} > D_{V,DT80}$. The volatile content of the coal-topping semi-coke decreases and the fuel ratio increases with an increase of D_V. For Da-tong originated coal, when D_V is greater than 0.55, the fragrant structure features a conspicuous condensation polymerization reaction and the semi-coke structure also exhibits an obvious sequence phenomenon. **Key words**: raw coal pyrolysis degree, coal-topping semi-coke, substance composition, semi-coke structure

下吸式生物质气化炉气化性能研究 = **Study of the Gasification Performance of a Downdraft Type Biomass Gasifier** [刊,汉] JIN Liang, ZHOU Jin-song, WU Yuan-mou, et al (National Key Laboratory on Clean Utilization of Energy Source, Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). - 105 ~ 109

Biomass fixed bed gasification technology features such merits as a stable operation and capability to serve as a clean energy source, however, there exist also problems, namely, a low gasification efficiency and a low fuel gas heating value. With a downdraft type gasifier serving as an object of study, which adopts the centralized air feeding technology in the furnace and heat packaging technology in the reduction zone, the influence of the furnace temperature and equivalent ratio (ER) of air on the fuel gas composition, fuel gas heating value and gasification efficiency etc. was studied and a comparison and analysis was made with the research results achieved in the past. The test results show that the gasifier under discussion can guarantee to obtain a relatively high temperature both in the fur-