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FLUENT中煤粉燃烧飞灰含碳量数值模型的改进

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摘　要: 为了提高FLUENT软件对电站煤粉锅炉飞灰含碳量的预测精度,推导了考虑灰层扩散阻力的焦炭缩核燃烧模型,基于FLUENT软件提供的"多表面反应模型"框架,结合用户自定义函数技术对其自带的焦炭燃烧模型进行了改进。然后对某1 025 t/h电站锅炉分别采用自带和改进的焦炭燃烧模型进行模拟,并和测试结果进行了对比。结果表明:自带模型由于忽略了灰层对燃烧气体的扩散阻力,求得的飞灰含碳量仅为0.1%,改进模型求得的飞灰含碳量为3.1%,与测试结果2.2%更为接近;自带模型和改进模型求得的炉膛出口O_2体积百分比分别为3.0%和3.3%,误差在±10%范围内。

关　键　词: 电站锅炉; 煤粉燃烧; 飞灰含碳量; 缩核模型

中图分类号: TK229.6　　**文献标识码**: A

引　言

随着CFD技术的发展,主流商业软件如FLUENT中已经自带煤粉燃烧模型,用户无需编程即可直接使用。过去十年中,已有很多文献介绍了关于FLUENT软件成功运用于电站煤粉锅炉NO_x减排[1-3]、富氧燃烧[4]、稳定性改造[5],混合燃料掺烧等领域的案例[6]。然而,关于利用FLUENT软件计算飞灰含碳量的研究鲜有报道,原因是FLUENT自带的焦炭燃烧模型存在一定的局限性,对焦炭燃烧的燃烧进程预测大多存在过快的现象。分析FLUENT用户手册焦炭燃烧模型可知[7],由于煤粉直径都很小,燃烧过程中形成的灰层很薄,FLUENT忽略了燃烧气体穿过灰层所受到的额外的阻力,从而使气体较易到达炭核表面与焦炭反应,导致所预测的焦炭反应速度过快。

为了能更准确预测飞灰含碳量,本研究放弃煤粉燃烧计算时普遍采用的概率密度函数(pdf)结合"动力/扩散控制"模型[8-10],推导了考虑灰层扩散阻力的焦炭缩核燃烧模型,并基于FLUENT软件提供的"多表面反应模型"框架,利用FLUENT软件的用户自定义函数技术对自带的焦炭燃烧模型进行了改进。然后对某1 025 t/h电站锅炉分别采用自带和改进的焦炭燃烧模型进行模拟,并将结果和测试结果进行了对比。

1　带灰层扩散阻力的焦炭燃烧模型

如图1所示,直径为d的焦炭颗粒燃烧时(此时水分、挥发份已析出完毕),最外层会形成一层气膜,往里是多孔灰层,中间为未燃烧的碳核,直径为d_c。随着燃烧的进行,灰层慢慢变厚,d_c慢慢变小,直到未燃烧碳核完全燃尽$d_c=0$为止。

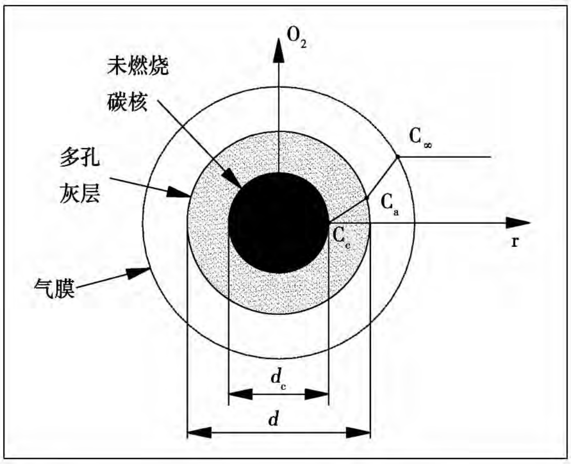

图1　带灰层扩散阻力的焦炭缩核模型示意图
Fig. 1 Schematic diagram of the model controlling the core shrinkage of coke with the dispersion resistance of the ash from its layer being considered

以氧气和焦炭反应为例,假定氧气和焦炭反应全部生成CO,即$C+0.5O_2 \rightarrow CO$。氧气要到达颗粒中心与未燃烧的碳核反应,必须穿透颗粒表面的气膜和多孔的灰层,氧气在穿透气膜和灰层的过程中

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浓度会逐渐降低。假定气膜外表面即气相空间中的氧气浓度为 C_∞，灰壳外表面的氧气浓度为 C_a，碳核外表面的氧气浓度为 C_c。

氧气的消耗速率与碳核表面积，动力速率以及表面的氧气浓度成正比：

$$R_{O_2} = \pi d_c^2 k_r C_c \tag{1}$$

则焦炭的燃烧速率为：

$$R_{char} = 2M_{char} R_{O_2} / M_{O_2} \tag{2}$$

式中：k_r—动力燃烧速率，m/s，与气相和颗粒温度有关，$k_r = AT_g \exp[-E/(RT_p)]$；$A$—指前因子，m/(s·K)；$E$—活化能，J/kmol；$T_p$—颗粒温度，K；$T_g$—气相温度，K；$M_{char}$—焦炭的原子量；$M_{O_2}$—氧气的分子量。

模型计算中，各表面反应的参数如表 1 所示。

表 1　各表面反应的参数[1]

Tab. 1 Parameters of the reaction on various surfaces

表面反应	$A/m\cdot(sK)^{-1}$	E/R(K)
$C+0.5O_2 \rightarrow CO$	2.3	11 100
$C+CO_2 \rightarrow 2CO$	3.42	15 600
$C+H_2O \rightarrow CO+H_2$	1.33	17 700

此外，按照斐克传质定律，灰层中的氧气质量流量即氧气的消耗速率[7]：

$$R_{O_2} = 4\pi r^2 D_{ash}(dC/dr) \tag{3}$$

式中：D_{ash}—氧气在灰层中的扩散系数，m^2/s，可按经典的多孔介质中的扩散系数公式来计算，即 $D_{ash} = (\varepsilon/\tau^2)\cdot(D_k^{-1}+D_0^{-1})^{-1}$；$\varepsilon$—灰层孔隙率；$\tau$—曲折率；$D_k$—努森扩散系数，$m^2/s$；$D_0$—分子扩散系数，$m^2/s$。

对式(3)分离变量并积分得：

$$\int_{0.5d_c}^{0.5d} R_{O_2} r^{-2} dr = \int_{C_c}^{C_a} 4\pi D_{ash} dC$$

$$\Rightarrow R_{O_2} = \pi D_{ash} \frac{2d_c d}{d-d_c}(C_a - C_c) = \pi k_{ash} d_c d (C_a - C_c) \tag{4}$$

式中：灰层扩散速率 $k_{ash} = D_{ash}/L_{ash}$，m/s；灰层厚度 $L_{ash} = 0.5(d-d_c)$，m。

氧气反应速率还应等于气膜中氧气质量流量：

$$R_{O_2} = \pi d^2 k_m (C_\infty - C_a) \tag{5}$$

式中：k_m—气膜扩散速率，m/s。采用经典的气流外掠圆球的关联式计算[7]，即 $Sh = k_m d/D = 2.0 + 0.6 \times Re^{1/2}Sc^{1/3}$。

综合式(1)、式(2)、式(4)、式(5)，消去 C_a 和 C_c 得：

$$R_{char} = 2\pi d^2 \frac{M_{char}}{M_{O_2}} C_\infty k$$

其中，k 为焦炭反应总体速率系数，

$$k = \frac{1}{k_m^{-1} + (d/d_c)k_{ash}^{-1} + (d/d_c)^2 k_r^{-1}}$$。

令碳核与颗粒直径比 $Y = d_c/d$，$Y \in [0,1]$，则焦炭反应速率系数：

$$k = \frac{Y^2}{Y^2 k_m^{-1} + Y k_{ash}^{-1} + k_r^{-1}} \tag{6}$$

灰层尚未形成时，$Y=1$，$L_{ash}=0$，$1/k_{ash}=0$，于是 $k = (k_m^{-1}+k_r^{-1})^{-1}$，表达式退化为常规的“动力/扩散控制”模型。而当碳核接近完全燃尽时，$Y=0$，于是 $k=0$，这样就体现了随着灰层的增厚，焦炭燃烧越来越困难的真实情况。

未燃烧碳核直径 d_c 的表达式可以根据燃烧过程中的灰份守恒求出，即：

初始时刻灰质量 = 燃烧过程中颗粒总质量 − 未燃烧碳核内焦炭质量

$$\Rightarrow \rho_{0,wvf}\left(\frac{\pi}{6}d_{0,wvf}^3\right)(1 - Y_{char,wvf}) = \rho\left(\frac{\pi}{6}d^3\right) - \rho_{0,wvf}\left(\frac{\pi}{6}d_c^{\ 3}\right)Y_{char,wvf}$$

$$\Rightarrow d_c = \sqrt[3]{\frac{\rho d^3 - \rho_{0,wvf} d_{0,wvf}^3 (1 - Y_{char,wvf})}{\rho_{0,wvf} Y_{char,wvf}}}$$

式中：$\rho_{0,wvf}$—焦炭燃烧初始时刻即干燥无挥发份颗粒的密度，kg/m^3；$d_{0,wvf}$—焦炭燃烧初始时刻的直径，m；$Y_{char,wvf}$—干燥无挥发份基下的焦炭质量分数。

2　计算实例

计算对象为某电站 1 025 t/h 亚临界锅炉，如图 2 所示。该炉膛设计采用的是一、二次风同心反切燃烧技术，四角切圆燃烧方式和供风喷口具体布置情况如图 3 所示。A、B、C、D、E 分别为 5 层一次风喷口(本次运行工况中 E 为关闭状态)，其它均为二次风喷口。表 2 – 表 4 分别给出了计算煤种成分分析、供风参数和计算时用的粒径分布。

主要模型设置：$k-\varepsilon$ 湍流模型，有限速率/涡耗散气相反应，P – 1 辐射模型，湿燃烧模型模拟水分蒸发过程，双竞争反应模型描述挥发份析出速率，多表面反应模型计算焦炭反应速率。根据前面所建立的带灰层扩散阻力的缩核燃烧模型，将该模型用自

定义颗粒表面反应速率的方式（调用用户自定义函数中的 DEFINE_PR_RATE 宏）覆盖 FLUENT 自带的表面反应速率模型。

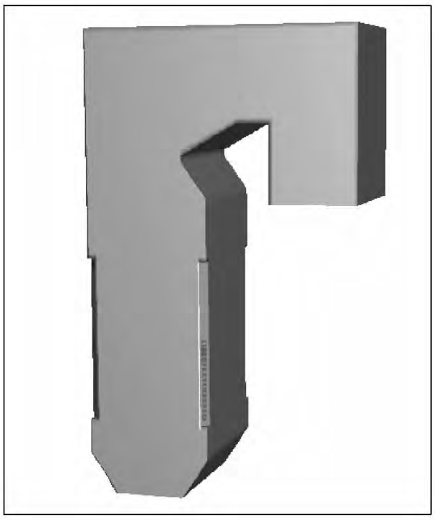

图 2　电站锅炉示意图

Fig. 2 Schematic diagram of a utility boiler

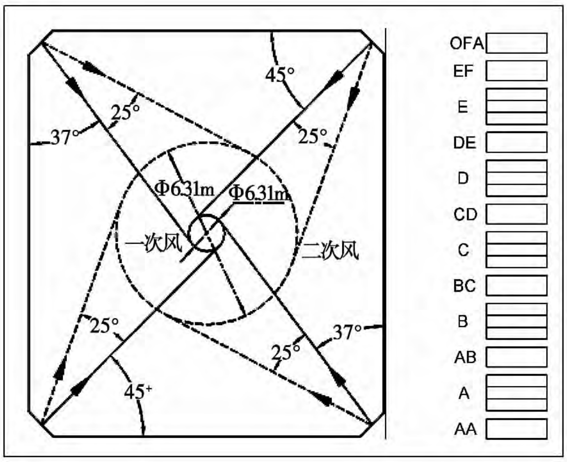

图 3　燃烧器和供风喷口布置示意图

Fig. 3 Schematic drawing showing the layout of burners and spouts for air supply

表 2　计算煤种成分分析

Tab. 2 Analysis of the composition of coal rank under the calculation

工业分析/%			元素分析/%					热值 $Q_{net,ar}$
M_{ar}	V_{ar}	FC_{ar}	C_{ar}	H_{ar}	S_{ar}	N_{ar}	O_{ar}	/MJ · kg^{-1}
16.45	23.56	52.80	61.74	3.35	0.63	0.69	9.95	24.074

表 3　供风参数

Tab. 3 Air supply parameters

空气过量系数	一次风速度	一次风温度	一次风风率	二次风速度	二次风温度
1.23	24 m/s	76.7 ℃	21.77%	47.6 m/s	320.6 ℃

表 4　粒径分布参数

Tab. 4 Parameters representing the distribution of particle diameters

分布方式	最小直径	最大直径	平均粒径	分布参数
Rosin - rammler	70 μm	200 μm	134 μm	4.52

3　计算结果

表 5 给出了 FLUENT 自带的焦炭燃烧模型和改进模型与测试结果的对比。可以看出，自带模型由于忽略了灰层对燃烧气体的扩散阻力，求得的飞灰含碳量仅为 0.1%，几乎完全燃尽，与测试结果 2.2% 有本质区别。而改进模型求得的飞灰含碳量为 3.1%，与测试结果较为接近。此外，自带模型和改进模型求得的炉膛出口 O_2 体积百分比分别为 3.0% 和 3.3%，与测试结果 3.2% 都比较接近，一个略偏低，一个略偏高，都在 ±10% 误差范围内，完全可以接受。

表 5　自带模型和改进模型的飞灰含碳量与测试结果对比

Tab. 5 Comparison of the carbon contents of flying ash calculated by using the built-in model and the improved one with the test results

	测试结果	自带模型	改进模型
飞灰含碳量	2.2 %	0.1 %	3.1 %
出口 O_2 体积百分比	3.2 %	3.0 %	3.3 %

图 4 和图 5 分别为自带模型和改进模型算出的温度场分布，可以看出，由于自带模型的焦炭燃烧速率过快，在接近煤粉喷口的地方温度就迅速达到 1 902 K，到接近炉膛出口，由于煤粉已经基本燃尽，不再释放热量，温度下降到 1 079.7 K。相比之下，改进模型的焦炭燃烧稍慢，但更加持久，在炉膛中心最高温度也就 1 713.4 K，而接近炉膛出口时由于焦炭尚未燃尽，尚可释放化学能，温度为 1 117 K，比自带模型要高约 40 K。由此可见，加入了灰层扩散阻力的新模型使焦炭整个燃烧过程变得匀速而持久。

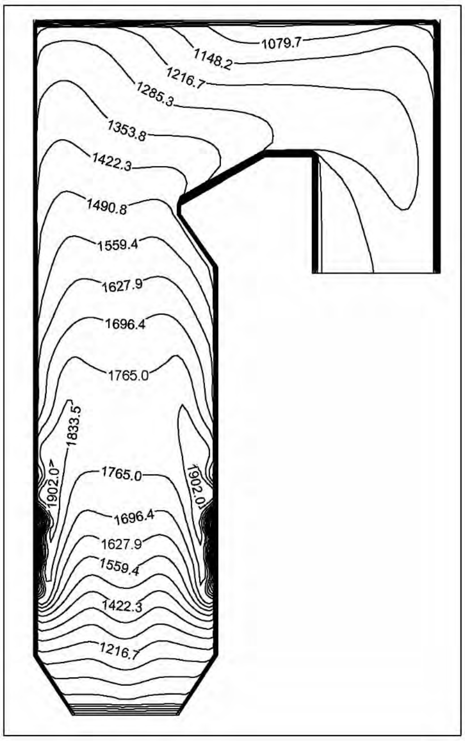

图 4　自带模型的温度场分布(K)

Fig. 4 Distribution of the temperature field calculated by using the built-in model (K)

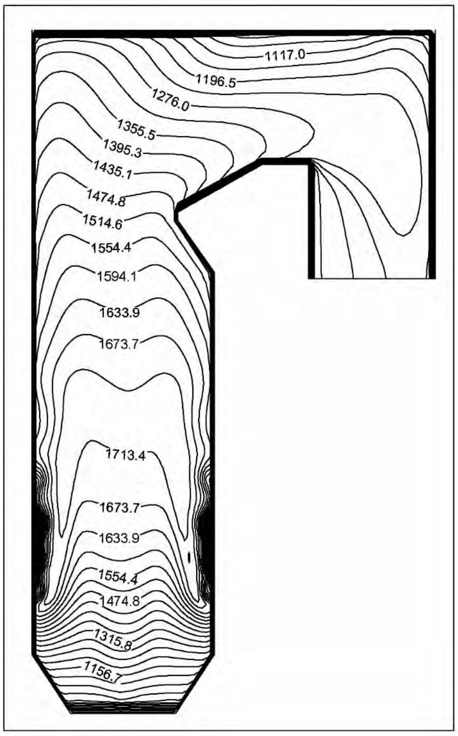

图 5　改进模型的温度场分布(K)

Fig. 5 Distribution of the temperature field calculated by using the improved model (K)

图 6 和图 7 分别为自带模型和改进模型的 D 层燃烧器横截面上的速度场。可以看到，自带模型该截面上的最高速度为 34.85 m/s，较改进模型的 33.34 m/s 要大。这是由于自带模型焦炭燃烧较快，局部气体温度更高(如图 4 和图 5 所示)，所以剧烈的气体膨胀引起更高的气流速度。

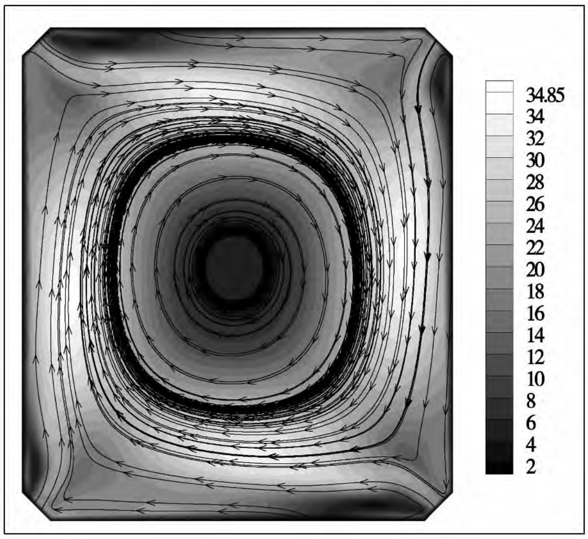

图 6　自带模型的速度场(m/s)

Fig. 6 Velocity field calculated by using the built-in model(m/s)

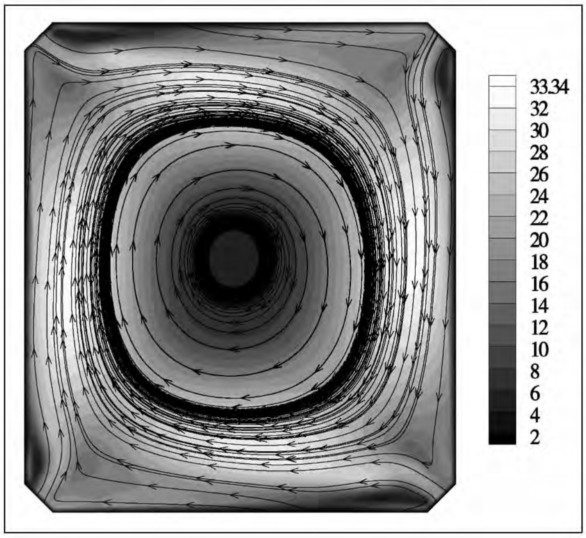

图 7　改进模型的速度场(m/s)

Fig. 7 Velocity field calculated by the improved model(m/s)

4 结论

为了考察改进模型的准确度,对某1 025 t/h锅炉分别用自带焦炭燃烧模型和改进模型进行试算,结果表明:

(1) 自带模型由于忽略了灰层对燃烧气体的扩散阻力,求得的飞灰含碳量仅为0.1%,改进模型求得的飞灰含碳量为3.1%,与测试结果2.2%更为接近。可见,改进模型修正了自带模型容易"完全燃尽"的弊端,飞灰含碳量更加符合实际情况。

(2) 自带模型和改进模型求得的炉膛出口O_2体积百分比分别为3.0%和3.3%,与测试结果3.2%都比较接近,误差在±10%范围内。

(3) 与自带模型相比,改进模型预测的炉膛温度场分布更均匀,炉膛中心最高温度较低而炉膛出口温度更高。

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(丛 敏 编辑)

key to the capacity expansion of the boiler. **Key words**: circulating fluidized bed, large-sized orientation, heating surface, thermal matching

蒸汽疏水阀门内漏量定量诊断方法研究 = Study of the Methods for Quantitatively Diagnosing the Inner Leakage Flow Rate of a Steam Trap [刊,汉] LIU Yang, LI Lu-ping, LIU Gong-chun, HUANG Zhang-jun (College of Energy Source and Power Engineering, Changsha University of Science and Technology, Changsha, China, Post Code: 410014), KONG Hua-shan, DENG You-cheng (Hunan Hongyuan High Pressure Valve Co. Ltd., Zhuzhou, China, Post Code: 412100) //Journal of Engineering for Thermal Energy & Power. -2014, 29(3). -309-314

Through a simulation calculation of the leakage flow rate of a valve, the authors obtained the variation law governing the changes of the tube wall temperature characteristic parameter of the drainage pipeline before the valve with the parameters of the working medium leaked, leakage flow rate, inner diameter of the tubes, tube wall thickness, insulation layer thickness and ambient temperature. Calculated by using a linear regression model, the authors also obtained a quantitative correlation formula between the tube wall temperature and the leakage flow rate at the point under discussion. In combination with the quantitative correlation formula, the authors also formulated a standard for quantitatively diagnosing the inner leakage flow rate of a valve and checked by using the test data published by the literature. The test results show that the correlation formula has sufficient accuracy and can be used for diagnosing any inner leakage fault of a steam trap. **Key words**: leakage flow rate, tube wall temperature, least square method, quantitative correlation formula

FLUENT **中煤粉燃烧飞灰含碳量数值模型的改进 = Improvement of the Numerical Model for Determining the Carbon Content of Flying Ash During Combustion of Pulverized Coal Contained in the Software Fluent [刊,汉]** CHEN Shi-he, ZHU Ya-qing, LUO Jia (Guangdong Power Grid Corporation, Academy of Electric Power Sciences, Guangzhou, China, Post Code: 510080), JI Jun-jie (Shanghai Kaili Research and Development Center, Shanghai, China, Post Code: 201206) //Journal of Engineering for Thermal Energy & Power. -2014, 29(3). -315-319

To enhance the precision predicting the carbon content of flying ash from a pulverized coal-fired boiler in a power plant by using the software Fluent, deducted was the core shrinkage model for coke with the dispersion resistance in the ash layer being taken into account and improved was the coke combustion model contained in the software Fluent by itself based on the "multiple surface reaction" framework provided by the software Fluent and in combination with the user defined function technology. On this basis, the self-contained and improved combustion model for coke

were used respectively to simulate a 1 025 t/h utility boiler and the simulation results were contrasted with the test ones. It has been found that due to the dispersion resistance of the ash layer to the combustion gas ignored by the self-contained model, the carbon content of flying ash thus obtained is only 0.1% while that obtained by using the improved model is 3.1%, the latter is closer to the test result 2.2%. The oxygen volumetric percentages at the outlet of the furnace obtained by using the self-contained and improved model are 3.0% and 3.3% respectively, thus the error is in a range of ±10%. **Key words:** utility boiler, combustion of pulverized coal, carbon content of flying ash, core shrinkage model

基于可视图网络节点重要性度量的离心泵振动故障诊断方法 = Method for Diagnosing the Vibration Fault of a Centrifugal Pump Based on the Visual Graph Network Node Importance Measure **[刊，汉]** SUN Bin, LIANG Chao, CUI Bin-bin (College of Energy Source and Power Engineering, Northeast University of Electric Power, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2014, 29(3). -320 -325

In the light of the nonlinear and unsteady characteristics of the vibration signals from a centrifugal pump, proposed was a method for diagnosing a fault of a centrifugal pump based on the visual graph network node importance measure (shortly referred to as visual graph network). A network was built by using the visual graph method and its characteristic parameters were extracted from the network. An analysis of the four kinds of network of the centrifugal pump, i. e. normal, non-aligned, non-balanced and loosened in the foundation, came to a conclusion that more accurate network information can be extracted from the visual graph network than from the relevant coefficient network and the former can be used to more accurately diagnose and analyze any fault of the centrifugal pump. By measuring the important nodes of the network, the authors obtained comprehensive evaluation results of the importance of the nodes in the network. The BC (betweenness centrality) index was used to diagnose fault, the correct percentage of a diagnosis can be up to 98.7%, more applicable for fault diagnosis compared with other indexes. It has been found that the method based on the visual graph and network node importance measure can diagnose more accurately any vibration fault of a centrifugal pump. **Key words:** complex network, visual graph, node importance, fault diagnosis

火电机组冷却塔变工况特性研究 = Study of the Off-design Operating Condition Characteristics of a Cooling Tower in a Thermal Power Generator Unit **[刊，汉]** XIA Lin, LIU De-you, DING Wei, HE Da (College of Water Conservation and Hydropower, Hohai University, Nanjing, China, Post Code: 210098) //Journal of Engineering for Thermal Energy & Power. -2014, 29(3). -326 -332

Based on the theory for soft measuring the air speed entering into a cooling tower and the real-time measured data of