第 26卷第 3期
2011年 5月
热 能 动 力 工 程
JOURNAL OF ENGINEERING FOR THERMAL ENERGY AND POWER
Vol.26, No.3
May, 2011

文章编号：1001－2060(2011)03－0351－03

主蒸汽压力与热耗修正曲线的变工况计算法

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摘 要：机组实际运行中，主蒸汽压力不可避免地偏离基准值而影响机组的热耗率。本研究以汽轮机变工况理论为基础，结合热力系统计算，采用 MATLAB编程，以某 600 MW凝汽式机组为例，计算得到了该机组在 THA工况下的主蒸汽压力与热耗修正曲线。主蒸汽压力的计算区间为 16.0～17.3 MPa，与汽轮机制造厂提供的热耗修正曲线对比，随着主汽压偏离设计值 16.7 MPa越大，热耗率的计算值与设计值的误差就会增大，当主汽压为 16.0 MPa时，误差达到最大，为 0.045%，但已完全能够满足工程实际的需要。结果表明本方法具有一定的计算精度，简单实用。

关 键 词：主蒸汽压力；汽轮机变工况；热耗修正曲线
中图分类号：TK269　　文献标识码：A

引 言

在机组实际运行中，主蒸汽压力经常会发生波动而偏离设计值[1]，确定机组主蒸汽压力变化对能耗影响的方法主要有特性试验法、特性曲线法和偏导原理算法[2]。本研究拟采用按抽汽口划分级组的方法，是以汽轮机变工况理论为基础，结合热力系统计算，假设调节级阀门开度不变，保持机组主蒸汽温度、再热蒸汽温度和背压不变，则机组出力发生变化，以此来计算并绘制主蒸汽压变化与热耗修正曲线。并以东汽 300 MW机组为例进行验证，结果表明该方法计算精度较高，能满足现场人员快速核算热耗修正曲线的要求。

1 主蒸汽压力变工况计算模型

1.1 初压变化对主蒸汽流量的影响

因调节阀开度不变，可以认为整个汽轮机的通流部分面积不变，弗留格尔公式能应用到调节级前，即：

$$\frac{D_{01}}{D_0}=\frac{\sqrt{p_{01}^2-p_{c0}^2}}{\sqrt{p_0^2-p_{c0}^2}}\sqrt{\frac{T_0}{T_{01}}} \quad (1)$$

式中：D_0、p_0、T_0、p_{c0}—基准工况下的主蒸汽流量，kg/h；压力，MPa；温度，℃以及排汽压力，kPa。下标 0和 1—变工况前后参数。

考虑到 $p_0 \gg p_{c0}$，$p_{01} \gg p_{c0}$，且 $T_0=T_{01}$，故式(1)可以化简为：

$$D_{01}=D_0\frac{p_{01}}{p_0} \quad (2)$$

1.2 初压变化对调节级的影响

调节级特性曲线是按额定参数绘制的。机组运行中，当主蒸汽参数偏离额定参数时，在同一压比条件下，因理想焓降不同，调节级各热力参数也不同，则使原已绘制的通用曲线不能再用。但对于滑压运行机组，调节级通用曲线是可以应用的，无须修正[3]。

若保持调节级开度不变，主蒸汽压力在一个小范围内的波动，相当于滑压运行，故可以利用调节级特性曲线进行调节级的变工况计算[4～5]，确定出变工况下的调节级效率 η_{ti}和调节级后焓 h_{ti}。

1.3 各抽汽口参数和排汽焓的确定

在热力系统变工况计算中，首先要确定各抽汽口的蒸汽参数，并在 h－s图上绘制汽轮机变工况下的汽态线。本方法按抽汽口划分级组，应用弗留格尔公式计算各抽汽口压力。对于凝汽式机组，抽汽区段之间的级组压比总是很小，忽略温度项的影响，则有：

$$p_{r1}=p_{r0}\frac{D_{r1}}{D_{r0}} \quad (3)$$

式中：p_r—第 r级组前压力，即第 r抽汽口压力，MPa；D_r—级组流量，kg/h。

变工况计算时，可以认为中间级的效率不变，则根据基准工况下相邻两抽汽口之间的级组效率计算变工况后各抽汽口的焓值。基准工况下级组 i的相对内效率 η_{i0}为[5]：

$$\eta_{i0}=\frac{h_{10}-h_{20}}{\Delta h_{t0}} \quad (4)$$

收稿日期：2010－06－04　修订日期：2010－06－25
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式中：h_{10}、h_{20}、Δh_{0}— r级组前后蒸汽焓值，kJ/kg；理想比焓降，kJ/kg。

变工况后r级组出口蒸汽焓值，即r+1级抽汽焓值计算式为：

$$h_{21}=h_{10}-\eta_{r0}\Delta h_{01} \tag{5}$$

式中：Δh_{01}可以根据级组前压力和焓值以及级组后压力在水蒸气图表中求得。

对于末级组，在得到变工况下级组前参数、级组流量和排汽压力的前提下，进行变工况计算[6]，得到初压变化后的排汽焓值h_{c1}。

1.4 回热系统各汽水参数的确定

本计算方法在确定回热系统各点汽水参数时不考虑加热器变工况，各加热器上、下端差和抽汽压损可认为近似不变。根据端差定义以及已知的给水泵和凝结水泵出口压力，即可确定变工况下各加热器出口水温、水焓以及疏水的温度和焓值。

1.5 辅助汽水参数和流量的确定[7]

热力系统中辅助成分很多，应区别处理，以保证计算的可靠性。对于轴封、门杆漏汽，其参数应视来源处参数变化而变化，其份额可根据基准工况下的热力系统热平衡和质量平衡来确定。其它的小汽水流量和参数也可进行类似的处理。

2 热力系统热经济性状态方程

热力系统状态方程包括：热力系统汽水分布方程、汽轮机功率方程、汽轮机热耗量方程。

2.1 热力系统汽水分布方程

当热力系统的结构参数和热力参数确定之后，则汽水分布方程就被确定了，可以用以下矩阵方程表示[9~10]：

$$[A][D]+[A_f][D_f]+[A_c][D_c]+[\Delta Q]=D_0[\tau] \tag{6}$$

2.2 汽轮机功率方程

由工质在整个循环过程中的质量平衡与能量平衡得到汽轮机功率方程：

$$P_0=D_0(h_0+\sigma-h_c)-[D_i]^T[\tilde{h}_i^c]-[D_u]^T\times[\tilde{h}_u^c]+D_{rs}(h_{zr}-h_c) \tag{7}$$

式中：σ—1 kg工质在再热器中的吸热量，kJ/kg；D_i、h_i—各级抽汽流量，kg/h，比焓，kJ/kg；D_u、h_u—离开通流部分的各辅助蒸汽流量，kg/h，比焓，kJ/kg；D_{rs}、h_{zr}—再热喷水量，kg/h，再热蒸汽比焓，kJ/kg；再热前：$\tilde{h}_i^c=h_i+\sigma-h_c$，$\tilde{h}_u^c=h_u+\sigma-h_c$；再热后：$\tilde{h}_i^c=h_i-h_c$，$\tilde{h}_u^c=h_u-h_c$。

2.3 热经济性指标计算

汽轮机热耗量：

$$Q_0=D_0(h_0-h_{fw})+D_{zr}\sigma+D_f(h_f-h_{fw})+D_{ma}(h_{ma}-h_{fw}) \tag{8}$$

式中：D_f、h_f—连续排污扩容器产生的蒸汽量，kg/h，比焓，kJ/kg；D_{ma}、h_{ma}—补水流量，kg/h，比焓，kJ/kg。

汽轮机装置效率：

$$\eta_i=\frac{P_0}{Q_0} \tag{9}$$

发电热耗率：

$$q_0=\frac{3600}{\eta_i\eta_m\eta_g} \tag{10}$$

式中：η_m、η_g—机械效率，%、发电机效率，%。

3 变工况计算具体步骤

（1）初压偏离基准值后变为p_{01}，因调节阀开度不变，根据式（1）得到初压变化后的主蒸汽流量D_{01}。

（2）忽略调节级后温度变化的影响，由弗留格尔公式化简得到调节级级后压力正比于全机流量，则有：

$$p_{tj1}=p_{tj0}\frac{D_{01}}{D_0} \tag{11}$$

通过调节级变工况计算得到初压变化后的调节级效率η_{tj1}以及调节级级后比焓h_{tj1}。

（3）假设各级加热器抽汽系数不变，即$\alpha_{j1}=\alpha_{j0}$，α_{j0}为基准工况下的抽汽系数。计算变工况下汽机各级组（以抽汽口划分）通流部分流量D_{r1}：

$$D_{r1}=(1-\sum_{j=1}^{r}\alpha_{j1})D_{01} \tag{12}$$

（4）确定各级抽汽压力p_{r1}。对各级组应用弗留格尔公式，忽略温度的影响，可确定抽汽压力值为：

$$p_{r1}=p_{r0}\frac{D_{r1}}{D_{r0}} \tag{13}$$

再热蒸汽压力p_{zr1}确定也可用式（13）来计算，又再热温度不变，则由水蒸气性质表查得再热蒸汽焓值h_{zr1}。

（5）确定各抽汽口焓值。可做如下简化：认为变工况前后相邻两抽口的压比相等，忽略抽汽口温度的影响，则变工况前后相邻两抽口的理想比焓降相等，变工况后抽汽焓值可计算为：

$$h_{(j+1)1}=h_{j1}-(h_{j0}-h_{(j+1)0}) \tag{14}$$

式中: h_j、$h_{(j+1)1}$—变工况下第 j、$j+1$ 级抽汽的焓值。

对于第一级抽汽焓值, 可把调节级到第一抽汽口之间的通流部分看作一个级组, 则有:

$$h_{11}=h_{i1}-(h_{i0}-h_{10}) \tag{15}$$

中压缸第一级抽汽, 其焓值 h_{31} 的确定式为:

$$h_{31}=h_{z1}-(h_{z0}-h_{30}) \tag{16}$$

(6) 假设变工况前后抽汽管道压损相对变化率 δP_0 不变, 计算加热器汽侧压力 p_i:

$$p_i=(1-\delta P_0)p_1 \tag{17}$$

由水蒸气性质表得到加热器汽侧压力下的饱和水温度 t_i。

(7) 根据加热器的布置型式和各加热器的上下端差值, 基准工况下的给水泵出口压力和凝结水泵出口压力, 得到变工况后各加热器出口水焓以及疏水焓[8]。

(8) 根据加热器的型式及布置方式, 确定每个加热器的 q、γ、τ。列出变工况后的回热系统汽水分布矩阵方程, 即:

$$[A][D'_i]+[A_f][D_f]+[A_{c1}][D_{c1}]+[\Delta Q]=D_{01}[\tau_i] \tag{18}$$

算出各级抽汽量 D'_i, 则抽汽系数为:

$$\alpha'_i=D'_i/D_{01} \tag{19}$$

(9) 当条件 $\left|\dfrac{\alpha'_i-\alpha_i}{\alpha_i}\right|\leqslant\Delta\alpha_j$ 成立时, ($\Delta\alpha_j$ 为各级抽汽误差系数, 取 $\Delta\alpha_j=0.005$) 则假设的抽汽系数 α_i 是正确的。否则取 $\alpha_i=\alpha'_i$, 重复步骤 (3) ~ 步骤 (8), 直到满足条件为止。

(10) 计算初压变化后的汽轮机功率 P_1 和热耗量 Q, 热耗率 q_1, 热耗相对变化量 δq, 则

$$\delta q=\frac{q_1-q_0}{q_0} \tag{20}$$

3 实例验证

以哈汽 N600－16.7/537/537-I 型机组为例, 采用本方法计算并用 MATLAB 7.0 软件编程, 计算结果如图 1所示。

由图 1可以看出: 设计工况下, 初压对热耗的修正曲线近似成直线关系, 随着主蒸汽压力的增加, 热耗是减少的, 热耗修正率为负值; 反之, 热耗修正率为正值。

主蒸汽压力计算区间为 16.0 ~17.3 MPa, 在额定初压 16.7 MPa附近的小范围内波动时, 计算值和设计值的热耗修正曲线重合度较好。在此区间外, 随着主蒸汽压力的升高或者降低, 计算值和设计值之间的误差就会增大, 当主汽压为 16.0 MPa时, 误差值达到最大为 0.045%, 但完全能够满足工程实际需要。

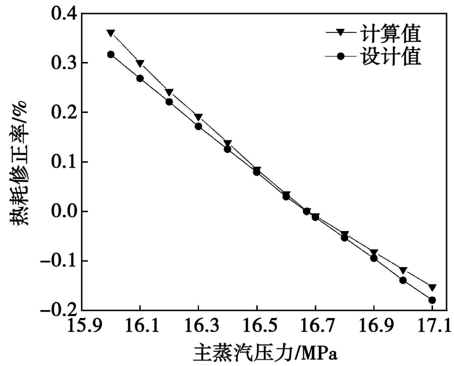

图 1　THA工况下初压与热耗的修正曲线

4 结　论

(1) 在计算主蒸汽压力与热耗修正曲线时以保持调节阀门开度不变, 其它参数不变为前提, 采用汽轮机变工况与热力系统状态方程相结合的方法, 有别于其它的计算方法。

(2) 用本方法计算得到的热耗修正曲线对比汽轮机厂家提供的曲线, 误差较小, 完全能够满足工程实际的需要。

(3) 对于某一特定的机组, 采用本计算方法绘制出的 THA工况下的初压与热耗修正曲线, 当主汽压力偏离设计值时, 通过该曲线能立刻查得热经济性的变化。

参考文献:

[1] 王艳军. 主蒸汽参数变化对机组功率影响的定量研究[J]. 热力透平, 2007, 36(3): 164－167.

[2] 王艳军. 初终参数变化对能耗影响的定量分析方法研究[D]. 保定: 华北电力大学, 2007.

[3] 江　宁, 曹祖庆. 调节级通用曲线的计算与应用[J]. 汽轮机技术, 3003, 45(1): 17－19.

[4] 李维特, 黄保海. 汽轮机变工况热力计算[M]. 北京: 中国电力出版社, 2001.

[5] 沈士一. 汽轮机原理[M]. 北京: 中国电力出版社, 2007.

[6] 程通瑞. 汽轮机末级变工况顺序计算方法的研究[J]. 汽轮机技术, 2008, 50(6): 425－427.

[7] 林万超. 火电厂热系统节能理论[M]. 西安: 西安交通大学出版社, 1994.

[8] 郑体宽. 热力发电厂[M]. 北京: 中国电力出版社, 2007.

[9] 张春发. 现行电力系统热经济性状态方程[J]. 工程热物理学报, 2001, 22(6): 665－667.

[10] 郭江龙. 基于能效分布矩阵方程的火电厂热力系统分析方法[D]. 保定: 华北电力大学, 2004.

(编辑　陈　滨)

Differential) Control Based on a Prediction Model[刊,汉] GUO Qi, YANG Xiu-li, REN Fang, et al (College of Environment and Chemical Engineering, Yanshan University, Qinhuangdao, China, Post Code: 066004)// Journal of Engineering for Thermal Energy & Power. —2011, 26(3). —343~346

In the light of such specific features of the temperature control over the clapping sleeve in an electrically-heated boiler as a big lagging and time variation etc., designed was a fuzzy-PID (proportional, integral and differential) controller based on a prediction model. After the above-mentioned prediction model has been established, by employing the fuzzy principle, the coefficient K value in the prediction model was adjusted, resulting in a great enhancement of the dynamic performance and steady state precision of the fuzzy-PID controller added by the prediction model. In Matlab, a simulation of the fuzzy-PID control was realized and also experimentally tested. From the simulation and experiment, it can be seen that the controller provided with the fuzzy control principle responds more quickly and has a smaller overshoot and greater capacity to resist the disturbance than a conventional PID controller. The test results show that the control effectiveness by adopting the control scheme in question is relatively good. Key words: prediction model, fuzzy-PID (proportional, integral and differential) control, simulation

多煤种混煤燃烧特性和动力学研究 = Study of the Combustion and Dynamic Characteristics of a Multiple Coal-rank-blended Coal[刊,汉] LIU Yan-jun, ZHOU Jie-min (College of Energy Science and Engineering, Central South University, Changsha, China, Post Code: 410083)// Journal of Engineering for Thermal Energy & Power. — 2011, 26(3). —347~350

By using a SDTQ-600 type temperature-difference-thermogravimetric analyzer, a thermogravimetric experiment was conducted of a blended coal composed of three single coal ranks in various proportions. The combustion and dynamic characteristics of the blended coal were studied. The test results show that the initial precipitation and ignition temperature of the volatile component of the coal will decrease with an increase of the proportion of the single coal rank with a highest volatile content and the maximum weight loss rate will increase with an increase of the carbon content of the coal. The Gorbatchev integral formulae and a dynamic model for primary reactions were used to seek solutions to the activation energy and frequency factor of the coal, during which the solutions are in relatively good agreement with the dynamic curves. When the coal ranks consisting of the blended coal are identical, the activation energy and volatile content of the blended coal as well as its activation energy and ignition temperature assume a good linear relationship. When the blended coal is in short of any single coal rank, such linear relationships will be destroyed. Key words: blended coal, activation energy, volatile content, thermogravimetric analysis

主蒸汽压力与热耗修正曲线的变工况计算法 = Method for Calculating Main Steam Pressure and Heat Rate Correction Curves Under Off-design Operating Conditions[刊,汉] ZHOU Lan-xin, HUA Min (College of Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003), WANG

Tong-bin, WEI Chun-zhi (Baoding Electric Power Vocational Technical College, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2011, 26(3). —351 ~353

During the practical operation of a steam turbine unit, the main steam pressure inevitably deviates from its reference value and affects the heat rate of the unit. Based on the off-design theory for steam turbines and in combination with the thermal system calculation, a program was designed by using the software MATLAB. With a 600 MW condensing type steam turbine unit serving as an example, the main steam pressure and heat rate correction curves for the unit were obtained through a calculation under the THA (turbine heat acceptance) operating condition. The main steam pressure ranged from 16.0 to 17.3 MPa. Compared with the heat rate correction curve provided by the steam turbine manufacturer, the error between the calculated value and the design one of the heat rate will increase with an increase of the main steam pressure deviation from the design value 16.7 MPa. When the main steam pressure is 16.0 MPa, the error attains its maximum value of 0.045%. However, this maximal error can completely meet the requirements of engineering practice. The research results show that the method in question has a certain calculation precision and is simple and practical. Key words: main steam pressure, off-design operating conditions of a steam turbine, heat rate correction curve

双进双出磨煤机降低磨煤电耗试验研究 = Experimental Study of a Dual Inlet and Outlet Coal Mill for Reducing Its Milling Power Consumption [刊, 汉] YUE Jun-feng, XIAO Jie, QIN Peng (Jiangsu Frontier Electric Power Technology Co. Ltd., Nanjing, China, Post Code: 211102), SU Zhong-ming (Huarun Electric Power Co. Ltd., Changshu, China, Post Code: 215536) // Journal of Engineering for Thermal Energy & Power. — 2011, 26(3). —354 ~357

On a dual inlet and outlet coal mill, an experiment for reducing the coal milling power consumption was performed and the influence of the bypass air quantity, steel ball load, steel ball distribution proportion and material level etc. factors on the coal milling power consumption was studied. The test results show that the coal milling power consumption gradually increases with an increase of the bypass air quantity, rising from 18 kW. h/t at a bypass air quantity of 10 t/h to 18.24 kW. h/t at a bypass air quantity of 26 t/h. The coal milling power consumption will first decrease and then increase with an increase of the steel ball load. When the steel ball load is 54 t/h, the power consumption will be minimized. It will gradually decrease with an increase of the material level, lowering from 17.44 kW. h/t at a material level of 400 mm to 16.45 kW. h/t at a material level of 600 mm. Among all the influencing factors, the steel ball load will play a decisive role in influencing the coal milling power consumption, the influence of the steel ball proportion and material level, however, can not be ignored. Key words: dual inlet and outlet coal mill, coal mill power consumption, steel ball

焙烧温度对甲烷低温燃烧用 Pd催化剂性能的影响 = Influence of the Calcination Temperature on the Per-