自然循环蒸发系统运行特性分析模型

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[摘要] 从基本物理方程出发,建立了自然循环蒸发系统的分布参数模型,并提出了基于流体微元追踪思想的数值计算方法。利用该模型既可进行蒸发系统的静态计算,又可实现系统过渡过程的数值分析。

关键词　电站锅炉　蒸发系统　数学模型
中图法分类号　TK224

0 前言

自然循环锅炉蒸发系统动态特性的的研究工作以往均侧重于上锅筒压力及水位响应特性的确定,在建模过程中一般取上锅筒压力为系统的集总参数且认为整个系统内的工质均处于该压力下的饱和状态,而工质的循环流量则按经验公式确定。当系统运行工况变动较大时,上述模型的精度一般难以保证,特别是对于标志着系统工作能力的工质循环流量的响应特性则更是如此。

随着我国电网峰谷差的逐年加大,一部分自然循环锅炉发电机组将以变压运行方式参与电网负荷调节。为保证机组调峰运行的可靠性,必须对机组在各种运行工况下工质循环流量的响应特性进行全面的计算分析。

1 过程数学模型

图 1为自然循环蒸发系统某段工质通道的物理模型,在常规的假定条件下[1],其过程数学模型可表述为:

$$\frac{\partial d}{\partial f} + \frac{\partial (d w)}{\partial y} = 0 \quad (1)$$

$$F d\left(\frac{\partial i}{\partial f} + w\frac{\partial i}{\partial y}\right) = q_2 + F\left(\frac{\partial p}{\partial f} + w\frac{\partial p}{\partial y}\right) \quad (2)$$

$$\partial p/\partial y + a w^2 d + d g = 0 \quad (3)$$

$$m_j c_j \frac{\partial t_i}{\partial f} = q_1 - q_2 \quad (4)$$

$$q_2 = f_2 T_2 (t_j - t) \quad (5)$$

$$\left.\begin{array}{l} d = d(P, t)\ (\text{单相工质}) \\ \text{或}\ d = d(P, x)\ (\text{双相工质}) \end{array}\right\} \quad (6)$$

为采用流体微元追踪计算方法[2,3]解决上述问题,可将方程 (1)、(2)变为:

$$D d/D f = - d/T_d \quad (1')$$

$$F d\cdot Di/Df = q_2 + F\cdot DP/Df \quad (2')$$

在以上诸式中,D/Df为流体参数的随体导数, $T_d = 1/(\partial w/\partial y)$, 为工质密度随流动时间 τ 变化的时间常数[3],其他符号的物理意义可参阅文后的符号表。

2 数值方法

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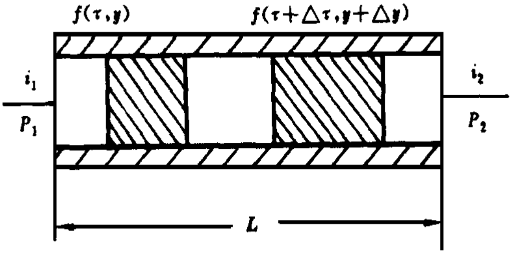

图 1　环节物理模型

2.1　工质参数的动态分布

给定某一时间步长Δf,若已知在 f时刻,在空间点 y处流体微元的密度为 d(f,y),由式(1′)知在 f+Δf时刻处于 y+Δy点的该流体微元的密度 d(f+Δf,y+Δy)应满足

$$\ln\frac{d(f+\Delta f,y+\Delta y)}{d(f,y)}=\int_{f}^{f+\Delta f}\frac{\partial w}{\partial y}\,\mathrm{d}f$$

近似认为在Δf时间内 $\partial w/\partial y$为常数且取

$$\frac{\partial w}{\partial y}=\frac{1}{\Delta y}[w(f+\Delta f,y+\Delta y)-w(f+\Delta f,y)]$$

注意到 $\Delta y=\Delta f\cdot w(f,y)$,则有

$$w(f+\Delta f,y+\Delta y)=w(f+\Delta f,y)+w(f,y)\cdot\ln\frac{d(f+\Delta f,y+\Delta y)}{d(f,y)}\qquad(7)$$

对单相区,可以认为工质焓的变化只取决于其受热情况。此时把式(2′)简化并与式(5)合并,得

$$T_t\cdot Dt/Df=-t+t_j\qquad(8)$$

上式中 $T_t=FdC_p/f_2T_2$,为工质温度随流动时间 f变化的时间常数,C_p为工质的定压比热。

对于两相工质,将其状态关系式

$$\frac{Di}{Df}=\frac{\partial i}{\partial p}\cdot\frac{Dp}{Df}+\frac{\partial i}{\partial x}\cdot\frac{Dx}{Df}$$

代入式(2)有

$$\frac{Dx}{Df}=[\frac{q_2}{f\,d}+(\frac{1}{d}-\frac{\partial i}{\partial p})\cdot\frac{Dp}{Df}]/(\frac{\partial i}{\partial x})$$

另由　$i=xi''+(1-x)i'$

得　$$\frac{\partial i}{\partial p}=x\frac{di''}{dp}+(1-x)\frac{di'}{dp}$$

$$\partial i/\partial x=i''-i'=r$$

从而有

$$\frac{Dx}{Df}=\frac{q_2}{Fdr}+\frac{1}{r}[\frac{1}{d}-x\frac{di''}{dp}-(1-x)\frac{di'}{dp}]\cdot\frac{Dp}{Df}\qquad(9)$$

若不计两相间的相对运动,则有汽水混合物的比容

$$g=1/d=g'+x(g''-g')$$

将上式代入式(9)经整理得

$$T_x\frac{Dx}{Df}=-x+u'/(u'-u'')\qquad(10)$$

其中　$$u'=g'(\frac{q_2}{F}+\frac{Dp}{Df})-\frac{di'}{dp}\cdot\frac{Dp}{Df}$$

$$u''=g''(\frac{q_2}{F}+\frac{Dp}{Df})-\frac{di''}{dp}\cdot\frac{Dp}{Df}$$

$T_x=\frac{r}{u'-u''}$,为两相工质含汽率 x随流动时间 f变化的时间常数。

由式(8)及式(10)知,对系统中的单相区和两相区,工质的能量方程具有如下的统一形式:

$$T_f\frac{Df(f,y)}{Df}=-f(f,y)+a\qquad(11)$$

其中的 $f(f,y)$代表 $t(f,y)$或 $x(f,y)$,而 T_f及 a则分别与式(8)及式(10)中的时间常数及源项相对应。

假定在Δf时间内 T_f及 a为常数,对式(11)积分得动态过程递推算式

$$f(f+\Delta f,y+\Delta y)=a-[a-f(f,y)]e^{-\Delta f/T_f}\qquad(12)$$

对单相段,若 $t(f,y)<t_{bh}[p(f,y)]$且 $t(f+\Delta t,y+\Delta y)\geqslant t_{bh}[p(f+\Delta t,y+\Delta y)]$,则加热水段长度 y_{rs}由下式确定

$$y_{rs}=y+[t_{bh}(P_c)-t(f,y)]\Delta y/\Delta t;$$

式中　$$p_c=\frac{1}{2}[p(f,t)+p(f+\Delta f,y+\Delta y)];$$

$$\Delta t=t(f+\Delta f,y+\Delta y)-t(f,y);$$

t_{bh}为相应压力下的饱和温度。

工质压力及密度的分布由动量方程及工

质的状态方程确定。

2.2　上锅筒压力的确定

上锅筒压力 P_{qb} 的变动速度根据上锅筒内能量、质量的收支不平衡程度及上锅筒热惯性系数 I_{qb} 的大小由下式确定[1]:

$$I_{qb}\,\mathrm{d}P_{qb}/\mathrm{d}f = \mathrm{E}(Di) - (\mathrm{d}'i' - \mathrm{d}''i'')/(\mathrm{d}' - \mathrm{d}'')\cdot \mathrm{E}D$$

式中的 $\mathrm{E}D$ 及 $\mathrm{E}(Di)$ 分别为单位时间内进入及流出上锅筒的工质流量及能量的代数和,即

$$\mathrm{E}D = D_{sm} + D_{qs} - D_{xj} - D_{qb}$$

$$\mathrm{E}(Di) = D_{sm}i_{sm} + D_{qs}i_{qs} - D_{xj}i_{xj} - D_{qb}i''$$

上锅筒的热惯性系数为

$$I_{qb} = V'_{qb}\left[\mathrm{d}'\cdot\frac{\partial i'}{\partial p} + \left(\frac{r\,\mathrm{d}''}{\mathrm{d}' - \mathrm{d}''}\right)\left(\frac{\partial \mathrm{d}'}{\partial p}\right)\right] + V''_{qb}\left[\mathrm{d}''\frac{\partial i''}{\partial p} + \left(\frac{r\,\mathrm{d}'}{\mathrm{d}' - \mathrm{d}''}\right)\left(\frac{\partial \mathrm{d}''}{\partial p}\right)\right] + C_j M_{yx}\frac{\partial t_{bh}}{\partial p}$$

上式中的 M_{yx} 为上锅筒的有效金属质量。

2.3　蒸发系统循环流量的计算

设蒸发系统上升管入口处工质压力为 $P_{SS}(f)$,上升管系高度为 H,记

$$\Delta p(f) = p_{qb}(f) - p_{ss}(f)$$

$$E(f) = g\int_0^H \mathrm{d}(f,y)\,\mathrm{d}y$$

$$R(f) = \int_0^H a\,\mathrm{d}(f,y)\,W^2(f,y)\,\mathrm{d}y$$

由动量方程式(3)有

$$\Delta p(f) + E(f) + R(f) = 0$$

令　$$Z_{dx}(f) = R(f)/\mathrm{d}_{ss}(f)W_{ss}^2(f)$$

上式中的 p_{ss} 为上升管入口处工质密度,W_{ss} 为该处的工质流速,即系统的循环流速

显然,$Z_{dx}(f)$ 为以入口工质参数计算的上升管系的瞬时等效阻力系数。这样,工质的循环流速可按下式近似递推计算

$$W_{ss}(f) = \left[-\frac{\Delta p(f+\Delta f) + E(f+\Delta f)}{Z_{dx}(f)\mathrm{D}_{ss}(f+\Delta f)}\right]^{\%}\qquad(14)$$

3　计算实例

利用上述模型对国产 200 MW机组的 HG－670/140－9型锅筒式锅炉蒸发系统在不同运行工况下的运行特性进行了计算分析。

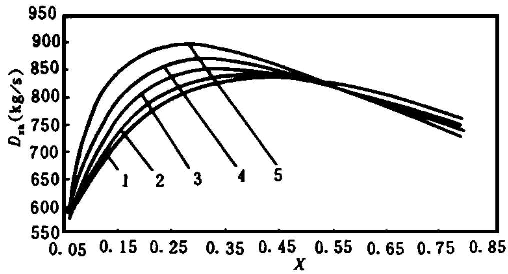

图 2　循环流量的静态特性

1. P_{qb} = 18MPa; 2. P_{qb} = 17MPa; 3. P_{qb} = 16MPa; 4. P_{qb} = 15MPa; 5. P_{qb} = 14MPa;

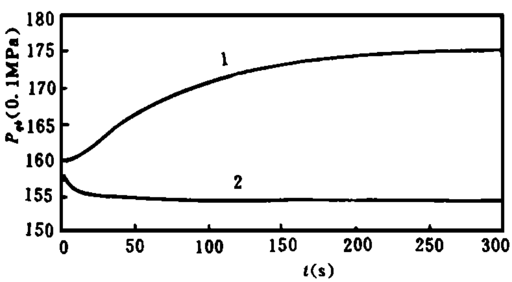

图 3　上锅筒压力的动态响应

1.热负荷阶跃增加;　2.汽机调门阶跃开大

图 2为在不同工作压力及热负荷(或上升管出口干度)下循环流量 D 的静态特性。显然,对于一定的 P_{qb},存在一个界限含汽率 x_{jx}。若 $x > x_{jx}$,循环流量将随热负荷的增加而减小,即系统丧失了自补偿能力。p_{qb} 越低则 x_{jx} 越小,且循环流量的大小对热负荷(或含汽率)的变动越为敏感。

图 3为炉内放热量和汽机阀门开度分别单一阶跃扰动时上锅筒压力的动态响应。可

见,在扰动发生初期,上锅筒压力对热负荷扰动的响应速度明显地小于其对汽机调门开度扰动的响应速度。

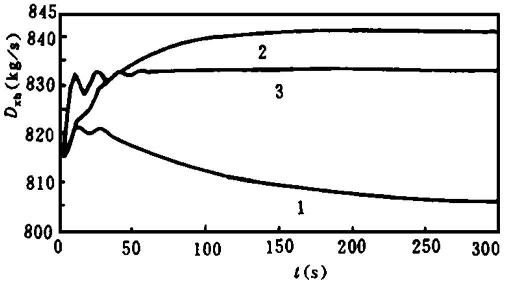

图 4 循环流量的动态响应

图 4为在不同运行方式下循环流量的响应特性。其中的曲线 1为炉内放热量单一阶跃增加后系统处于变压运行方式时循环流量的瞬态行为;曲线 2为热负荷增加后改变汽机调门开度以保证上锅筒压力基本恒定时循环流量的响应特性;曲线 3表示汽机调门阶跃开大后循环流量的过渡过程。可见,对于定压运行工况,循环流量随热负荷的增加而增加;当采用变压运行方式时,由于压力升高的影响使循环流量的响应特性变得比较复杂:在扰动发生初期,由于上升管系含汽率的增加导致循环流量很快加大;此后 P_{Φ} 的升高又削弱了系统的运动压头,从而循环流量开始回落,最后其终值低于初始循环流量。这种趋势显然不利于蒸发系统的安全运行。

此外,由图 4还可发现,由于沸腾系统中两相流体所固有的扰动传播时间滞后和反馈特性[4],在扰动发生初期,循环流量的变化具有一定的波动性。压力变动越快,循环流量的波动就越明显。

4 结束语

本文建立了自然循环蒸发系统分布参数模型。由于在数值计算过程中引入了流体微元追踪计算方法,从而使系统中单、双相环节的数学模型具有统一的模式,并且从式 (7)及式 (12)~ (14)中不难看出,利用该模型既可进行系统的静态计算 (如水循环计算),又可实现系统过渡过程的数值分析。

符号说明

D 工质流量　*F* 流通面积　*C* 比热　*V* 容积
g 重力加速度　*i* 工质焓　*p* 压力　*r* 汽化潜热
t 温度　*w* 流速　*x* 干度　*y* 长度坐标
f 时间坐标　d 密度　g 比容　T 换热系数
a 阻力系数　*m* 单位长度流道对应的 (金属) 质量
q 单位长度流道的换热量　*f* 单位长度流道的换热表面积
下标　1 管外侧　2 管内侧　j 金属　qb 汽包
rs 热水段　xj 下降管　qs 汽水导管
sm 省煤器　bh 饱和状态
上标　′ 饱和水　″ 饱和汽

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(复　编)

discusses the design philosophy of the modification scheme and proposes a new type of high-temperature boiler flue gas tube construction. **Key words** high-temperature boiler flue gas tube, failure analysis, structural design

模糊自组织神经网络在汽轮机转子故障诊断中的应用=(**Application of Fuzzy Self-organizing Neural Networks in a Steam Turbine Rotor Fault Diagnosis**) [刊,中]/Wang Jian, Jiang Dongxiang, Ni Weidou (Qinghua University)// Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 43~45

In the light of the problems involved in a steam turbine rotor fault diagnosis proposed in this paper is a new diagnostic method based on a fuzzy self-organizing neural network. The proposed method features a simple structural algorithm, supervision-free self-study and lateral thought association, etc. This highly effective method for turbine rotor failure classification has been verified in the course of its practical use. **Key words** steamt urbine totor, failure diagnosis, fuzzy mathematics, neural network

能源及化工过程中的事故仿真=(**Failure Simulation in Energy Sources and Chemical Engineering Processes**) [刊,中]/Xiao Lichuan, Xue Guoxin (Jiangsu Petrochemical Institute)// Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 46~48

After a discussion of the universal method for failure setting in energy sources and chemical engineering processes the authors come up with a transitional general function for the interface of failure status and normal operating condition. A generally applicable form of failure occurrence and an exit from ascertainment criteria are also given. Furthermore, other details concerning the failure entering form and its succession have been taken into account. **Key words** failure, simulation, transitional general function, failure ascertainment, failure succession

炉内冷态流场数值模拟算法讨论及验证=(**A Discussion and Verification of the Numerical Simulation of a Cold-state Flow Field in a Boiler**) [刊,中]/Sun Ping, Fan Jianren, Cen Kefa (Zhejiang University), Xie Hailong (Northeast Electrical Power Institute)// Journal of Engineering for Thermal Energy & Power. - 1998, 13(1) - 49~52

Studied in this paper are some convergence promotion methods for the simulation of flow fields in a boiler furnace by the use of a Simpler method and the specific features of Quicke scheme. Heating surfaces in the furnace are treated through the use of multi-hole rate in conjunction with resistance distribution. The calculated results agree well with experimental ones. **Key words** simulation of flow field, Quicke scheme, multi-hole rate

旋转机械振动故障的模糊诊断=(**Fuzzy Diagnosis of Rotating Machinery Vibration Faults**) [刊,中]/Ruan Yue, Xu Shichang (Harbin Institute of Technology)// Journal of Engineering for Thermal Energy & Power. 01998, 13(1). - 53~56

After making an analysis of the existing difficulties in the failure analysis of rotating machinery vibration failures this papr presents a mathematical model for conducting failure mechanism study and failure diagnosis. On the basis of symptoms asserting a positive and negative trend of the vibration failures proposed is a fuzzy recognition matrix of fault diagnosis with the realization of a complex failure diagnosis. **Key words** vibration failure, fuzzy diagnosis, mathematical model, rotating machinery

自然循环蒸发系统运行特性分析模型=(**A Model for Analysing the Operating Characteristics of a Natural Circulation Boiling System**) [刊中]/Wang Guangjun, Li Hongyuan (Northeast Electrical Power Engineering Institute)// Journal of Engineering for Thermal Energy & Power- 1998, 13(1). - 57~60

Proceeding from a basic physical equation a distribution parameter model of natural circulation boiling system was established and a numerical calculation method based on a fluid microelement tracing philosophy also proposed. By using this model it is possible to not only conduct the static-state calculation of the boiling system but also realize the numerical analysis of the system transition process. **Key words** utility boiler, boiling system, mathematical model

膜式水冷壁温度场分布的数值计算 = (**Numerical Calculation of the Temperature Field Distribution of a Membrance Water Wall**) [刊,中] /Sheng Chunhong, Chen Tingkuan (Xi′an Jiaotong University)// Journal of Engineering for Thermal Energy & Power.- 1998, 13(1). - 61~65

With the help of a finite difference method a temperature field distribution calculation is conducted of a membrane water wall, a tube wall with an irregular shape. In connection with the above-mentioned method used are an additional source item method, expansion zone method and zone separation method. "Finned tube temperature field calculation procedures" prepared by the use of the method described in the paper can be employed for the calculation of various kinds of operating conditions with the temperature deviation of the temperature field being converged to within 0.1℃. **Key words** memrane water wall, finite difference theory, temperature field

中间再热汽轮机调节系统响应特性的改善方法 = (**A Method for Improving the Response ChaRacteristice of an Intermediate Reheat Steam Turbine Control System**) [刊,中] /Dai Yiping, Yu Maozheng (Xi′an Jiaotong University)// Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 66~69

Through the study of response characteristics in the presence of local positive feedback action in the actuating mechanism of an intermediate reheat steam turbine governing system the authors have proposed an improved system with the use of a hydraulic feedback mechanism. A contrast analysis is made of the response characteristics of two kinds of systems. The system which employs the hydraulic feedback can effectively eliminate the positive feedback action present in the spring feedback system of a slide valve sleeve. This can lead to an improvement of the system response characteristics, thus enhancing the system stability and decreasing the dynamic overspeed of the turboset at full load rejection. **Key words** governing system, feedback, stability

解决供热汽轮机调速系统卡涩、负荷突变的措施 = (**Some Measures for the Prevention of Heat Supply Steam Turbine Governing System from Getting Stuck and Abrupt Load Changes**) [刊,中] /Li Baoyu, Gao Xiaoling (Harbin Turbine Co. Ltd.), Yang Quanhai, Nie Weidong (Huhehot Thermal Power Plant)// Journal of Engineering for Thermal Energy & Power. - 1998, 13(1). - 70~72

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