文章编号: 1001－2060(2007)03－0297－04

基于自抗扰的多变量解耦控制在球磨机的应用

马永光, 郝 娜, 李鹏飞, 李 妍
(华北电力大学 控制科学与工程学院, 河北 保定 071003)

摘 要: 火电站球磨机制粉系统是一个典型的三输入三输出的系统, 各变量之间严重耦合, 利用 PID 控制很难达到理想效果。针对这些特点, 将一种新型的控制策略—自抗扰控制器(Auto Disturbance Rejection Controller ADRC)和一种多变量解耦控制相结合应用到该系统中, 并对 ADRC 做了部分改进。针对某球磨机制粉系统, 设计了基于自抗扰的多变量控制系统, 并与反标架正规化(RFN)设计方法和 SMITH 预估补偿方法进行了比较, 仿真结果表明了本文所提出的控制算法的有效性、抗扰性及强鲁棒性, 因此该控制策略具有很高的工程实用价值。

关 键 词: 球磨机; 自抗扰控制器(ADRC); 解耦控制; 反标架正规化 RFN; SMITH 预估补偿法

中图分类号: TK229; TP13 文献标识码: A

引 言

钢球磨煤机是我国火电厂制粉系统中使用最多的磨煤设备, 占全国电厂磨煤机总数的 60%以上, 且广泛应用于其它行业。但是由于球磨机制粉系统具有强耦合、非线性、大迟延、大惯性的特点, 其自动控制问题一直未能很好解决。目前, 常规控制方案如 PID 控制方式往往达不到复杂的磨煤机系统的控制要求。针对该系统的强耦合特性, 文献[1～2]分别给出了反标架正规化(RFN)设计方法和逆奈奎斯特阵列(INA)法。而对于该系统的大延迟特性, 文献[3]采用 SMITH 预估补偿方法来解决。自抗扰控制器(ADRC)是近年提出的一种以 PID 为基础的非线性控制器, 它不依赖于受控对象的数学模型, 算法简单, 在未知非线性和不确定扰动作用下都能够保证控制精度。本文结合文献[3]多变量解耦控制理论, 将自抗扰控制用于球磨机制粉系统, 通过仿真试验证明该算法的可行性。

收稿日期: 2006－06－27; 修订日期: 2006－10－26

作者简介: 马永光(1964－), 男, 河北雄县人, 华北电力大学教授.

1 对象模型

火电厂球磨机制粉系统是一个典型的三输入—三输出的系统。其输入为给煤机转速 u_1、热风门开度 u_2、再循环风门开度 u_3, 输出为球磨机存煤量 H、磨出口温度 T、磨入口负压 P。例如国产 DPM320/580 球磨机, 采用前轴瓦震动信号来表示球磨机的存煤量, 这样可以克服风量对存煤量信号的影响, 该球磨机在稳定工作点附近的传递函数矩阵[4]:

$$\begin{bmatrix} H(s) \\ T(s) \\ P(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} =$$

$$\begin{bmatrix} \dfrac{0.1}{(20s-1)^2}e^{-90s} & 0 & 0 \\ \dfrac{-1.05}{180s+1}e^{-20s} & \dfrac{3.5}{(80s+1)^3} & \dfrac{-0.14}{(60s-1)^2} \\ \dfrac{-0.37}{100s+1}e^{-15s} & \dfrac{-20}{80s+1} & \dfrac{-0.18}{10s+1} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad (1)$$

2 球磨机自抗扰控制器的设计

2.1 自抗扰控制器的原理

以二阶自抗扰控制器的结构图来说明其原理, 如图 1 所示 ADRC 包括: 跟踪微分器(TD)、扩张状态观测器(ESO)、非线性反馈(NLSEF)等技术。自抗扰控制器的功能由以上 3 个环节共同作用形成: 用跟踪微分器来安排过渡过程并提取其微分信号; 用扩张状态观测器估计对象状态和不确定扰动作用; 安排的过渡过程与状态估计之间误差的非线性组合和扰动估计量的补偿来生成控制信号。

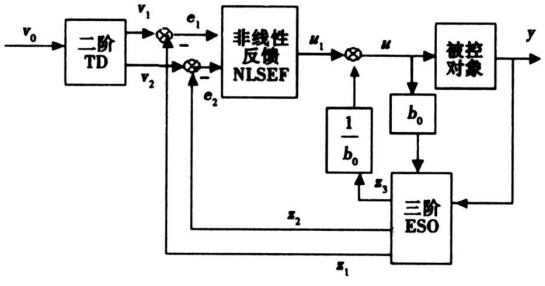


图 1 自抗扰控制器的基本结构

2.1.1 TD 模块的实现

通过对ADRC 控制低阶对象($n<3$)的仿真结果分析发现,TD 除了跟踪参考输入信号 $v_0(t)$, 安排预期动力学特性外, 其主要作用还在于柔化 $v_0(t)$ 的变化, 以减少控制过程输出的超调量。同时在实际工程应用中, 往往只需要构造满意的预期动力学特性, 勿需最优。因此, TD 可用某些结构简单的柔化环节来实现, 例如, 当被控对象的惯性或延迟较大时, 可将 TD 设计为线性惯性环节。本文借鉴文献[6]推荐的非线性控制逆系统方法中预期动力学方程的选取, 将TD 的传递函数设计为:

$$\frac{v_1(s)}{v_0(s)}=\frac{w^2}{s^2+2\xi ws+w^2}\left(\frac{\alpha w(n-2)}{s+\alpha w(n-2)}\right)^{n-2} \qquad (2)$$

式中: $v_1(s)$、$v_0(s)$—跟踪微分器的第一个输出和输入; n—被控对象的阶数; ξ—阻尼系数, 它决定了跟踪微分器响应过程的形状; w—角频率, 它决定了响应过程的快慢, 即跟踪的快慢。

2.1.2 ESO 模块的离散算法实现

$$\begin{cases} e(k)=z_1(k)-y(k) \\ z_1(k+1)=z_1(k)+h(z_2(k)-\beta_{01}\cdot fal(e(k),a_{01},\delta)) \\ z_2(k+1)=z_2(k)+h(z_3(k)-\beta_{02}\cdot fal(e(k),a_{02},\delta)+b_0u) \\ z_3(k+1)=z_3(k)-h\beta_{03}\cdot fal(e(k),a_{03},\delta)) \end{cases}$$

式中:

$$fal(e,a,\delta)=\begin{cases} |e|^a\,\mathrm{sign}(e), & |e|>\delta \\ e/\delta^{1-a}, & |e|\leqslant\delta \end{cases}, \quad \delta>0$$

其中, 扩张状态观测器 ESO 的状态变量 z_1、z_2 能很好地跟踪对象输出 y 及 y 的微分, 而 z_3 则能估计出系统加速度的实时作用量, 并反馈到控制量 u_1。

2.1.3 NLSEF 模块的离散算法实现

非线性控制律 NLSEF 的作用是生成一个控制量, 其实现过程如下:

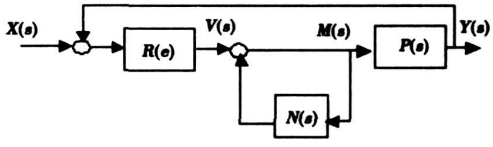
$$\begin{cases} e_1=v_1(k)-z_1(k) \\ e_2=v_2(k)-z_2(k) \\ u_1=\lambda_1 fal(e_1,a_1,\delta)+\lambda_2 fal(e_2,a_2,\delta) \\ u=u_1-z_3(k)/b_0 \end{cases} \qquad (3)$$

其参数 λ_1, λ_2 具有较为明确的物理意义, λ_1 表示比例增益, λ_2 表示微分增益, 它们的整定同 PD 控制器中的 P、D 整定, 相当于用 PD 控制器控制一个“积分串连型”的对象。

2.2 解耦设计结构

常规解耦方法可分为静态解耦和动态解耦。静态解耦方法适用于对象模型较精确, 在静态工作点附近线性度较好的环境, 它具有结构简单、实现容易的特点。由于钢球磨煤机是一个复杂的被控对象, 工作状态极不稳定, 所以静态解耦不适用于钢球磨煤机。动态解耦是在被控对象工作的全过程进行解耦, 在一定条件下有良好的解耦效果。解耦后的系统可按单回路的原则来整定自抗扰控制器的参数。

根据 Mesarovic 命题[7], 对于一个给定规范的被控对象, 当采用与之相反的另一种解耦环节结构时, 能使系统的解耦条件趋于简单。由 DPM320/580 球磨机对象数学模型知, 它是一个 P 规范耦合对象, 故本设计中采用 V 规范解耦环节, 而且将解耦环节置于控制器与对象之间, 解耦控制系统结构如图 2 所示。



$R(s)$— 控制器矩阵; $P(s)$— P 规范对象传递函数; $N(s)$— V 规范解耦环节矩阵

图 2 解耦控制系统结构

根据文献[3], 球磨机系统解耦环节矩阵可近似为:

$$N(s)=\begin{bmatrix} 0 & N_{12} & N_{13} \\ N_{21} & N_{22} & N_{23} \\ N_{31} & N_{32} & N_{33} \end{bmatrix}=$$

$$\begin{bmatrix} 0 & 0 & 0 \\ \dfrac{-0.3-21s+230s^2}{1+70s+633s^2} & 0 & \dfrac{0.04+6.4s+256s^2}{1+120s+3600s^2} \\ \dfrac{-2.06-5014s+116s^2}{1+107.5s+769s^2} & \dfrac{-11.1-111.1s}{1+8s} & 0 \end{bmatrix} \qquad (4)$$

2.3 控制结构图

自抗扰控制结构如图 3 所示, 其中: H_0 为存煤量设定值; T_0 为出口温度设定值; P_0 为入口压力设定值。ADRC1 按 $G_{11}(s)$设计为二阶自抗扰控制器, 其主要参数整定结果为 $w=0.5$, $\xi=0.9$, $\beta_{01}=10$,

$\beta_{02}=100$, $\beta_{03}=20$, $\lambda_1=0.45$, $\lambda_2=20$; ADRC2 按 $G_{22}(s)$设计为三阶自抗扰控制器, 主要参数整定结果为 $w=0.1$, $\xi=0.9$, $\beta_{01}=20$, $\beta_{02}=127$, $\beta_{03}=267$, $\beta_{04}=170$, $\lambda_1=50$, $\lambda_2=12\ 500$, $\lambda_3=14\ 000$; ADRC3 按 $G_{33}(s)$设计为一阶自抗扰控制器, 主要参数整定结果为 $\beta_{01}=10$, $\beta_{02}=10$, $\lambda_1=2$。为符合实际操作, 需要对控制量进行限幅。

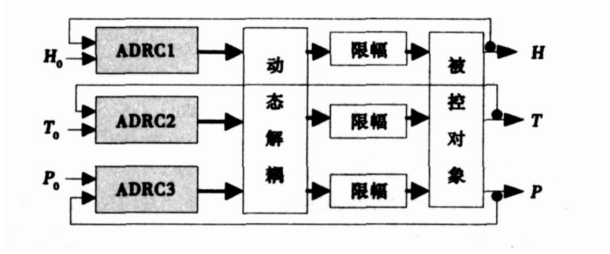


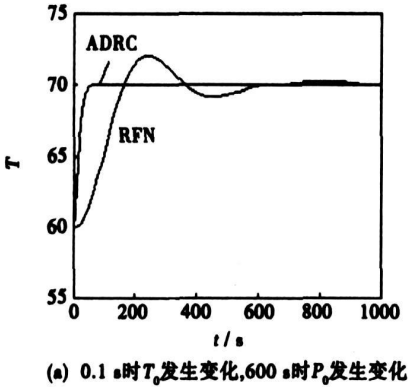
图 3　球磨机的 ADRC 控制系统

3　系统仿真试验

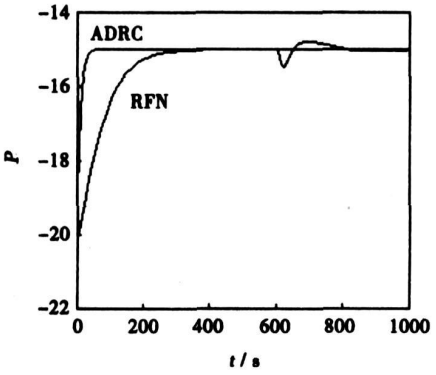
为了与其它控制策略比较和验证自抗扰控制器的控制效果, 本文将复现基于 RFN 方法对耦合回路的控制和 SMITH 预补偿方法存煤量回路的控制系统。

3.1　阶跃响应

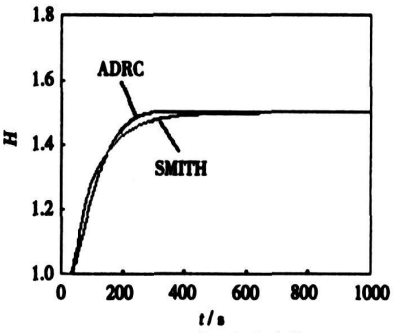
出口温度设定值 T_0 由 60 ℃变化为 70 ℃, 入口负压设定值 P_0 由－196.1 Pa 变化为－147 Pa, 存煤量设定值 H_0 由 1 t 变化为 1.5 t, 当系统分别发生上述扰动时, 系统的响应如图 4 所示。从图中可以看出, 通过动态解耦和 ESO 对外扰的补偿作用, ADRC 控制能较好的对球磨机制粉系统进行控制, 且性能要优于 RFN 和 SMITH 控制。



(a) 0.1 s时T_0发生变化,600 s时P_0发生变化



(b) 0.1 s时P_0发生变化,600 s时T_0发生变生

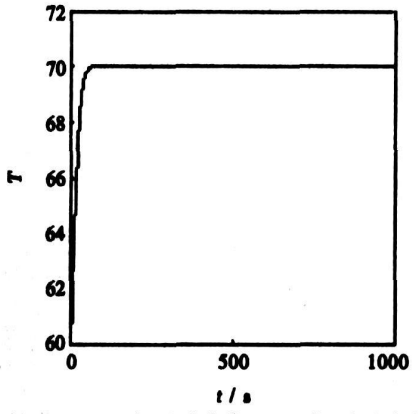


(c) 0.1s时H_0发生变化

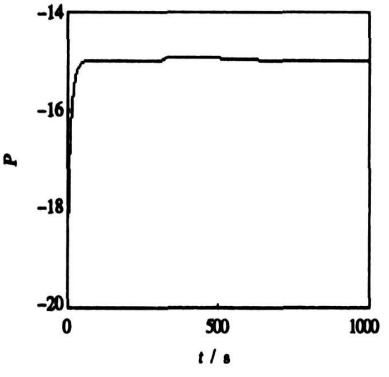
图 4　阶跃响应仿真曲线

3.2　抗扰试验

当 H_0 发生定值扰动时对 T 回路和 P 回路的影响如图 5 所示。



(a) 0.1 s时T_0发生变化,300 s时H_0发生变化



(b) 0.1 s时P_0发生变化,300 s时H_0发生变化

图 5　抗扰性仿真曲线

3.3 鲁棒性试验

球磨机的出口温度为高阶对象，式(1)中的传递函数式由实际高阶对象降阶简化所得。为此将传递函数 $G_{22}(s)$的阶数增加一阶，考虑到实际系统的工况变化，再将其增益增加 50%，用于检验控制系统的鲁棒性。仿真结果如图 6 所示，T_0 由 60 ℃阶跃至70 ℃，ADRC 的鲁棒性要优于 RFN。

$$G_{22}(s)=5.25/(80s+1)^4$$

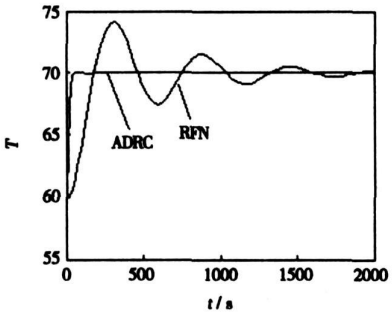


图 6 鲁棒性仿真曲线

4 结 论

介绍了自抗扰控制(ADRC)的原理和算法设计，并对其进行了部分改进。本文将 ADRC 与多变量解耦控制结合应用于球磨机制粉系统，并与文献[1]中的 RFN 和文献[3]中的 SMITH 方法进行比较，从仿真结果可以看出，ADRC 在耦合回路的控制品质要优于 RFN，在存煤量控制回路上的控制品质要优于 SMITH，并且在鲁棒性和抗干扰能力方面都显示出了优越的性能。因此，自抗扰控制器能有效地控制球磨机这类强耦合、非线性、大迟延的热工对象，并且该算法在多变量解耦控制系统中有良好的推广价值。

参考文献：

[1] 苏 杰，孙德立，曾 新. 球磨机控制系统的一种频域方法设计[J]. 华北电力大学学报，1998，25(3)：81－86.

[2] 田 沛，马 平，吕丽霞，等. 球磨机控制系统 INA 方法设计[J]. 华北电力学院学报，1994，21(1)：69－72.

[3] 谢克明，李国勇. 中储式制粉系统解耦控制系统[J]. 太原工业大学学报，1994，25(2)：17－21.

[4] 韩京清. 自抗扰控制器及其应用[J]. 控制与决策，1998，13(1)：19－23.

[5] 刘 翔，李东海，姜学智，等. 自抗扰控制器在高阶系统控制中的仿真研究[J]. 清华大学学报(自然科学版)，2001，41(6)：95－99.

[6] 李东海，姜学智，徐忠净，等. 一类不可逆系统的非线性控制及预期动力学方程的选取[J]. 控制与决策，1998，13(6)：686－689.

[7] MESAROVIC M D. The control of multivariable systems[M]. London：John Wiley，1960.

[8] 孙立明，李东海，姜学智，火电站球磨机制粉系统的自抗扰控制[J]. 清华大学学报(自然科学版)，2003，43(6)：779－781.

(编辑 渠 源)

新 机 组

第四代 LM2500 燃气轮机技术升级改进

据《Gas Turbine World》2005 年 11～12 月号报道，GE 公司升级改进的第四代 LM2500 燃气轮机(LM2500＋G4)在 2006 年投放市场。

最新的升级改进的 LM2500＋G4 燃气轮机具有 6 级或 2 级动力涡轮，对于工业应用该机能提供 8%～10%更多的输出频率，对于船舶推进能提供 5%～8%更多的辅出功率。

用于机械驱动时，该机的输出为 34 130 kW，效率为 39.8%；用于发电机组时，该机的输出为 33 394 kW，效率为 39.0%。

用于机械驱动方案的升级改进是适于增加燃气初温和压比、9%更多的输出功率、5%更高的质量流量和 2%更热的排气温度。

预期 LM2500＋G4 也将进入商船和海军推进系统市场。该燃气轮机实质上早已船用化，压气机部分使用不锈钢材料，涡轮部分使用了能承受船用环境的材料和涂层。高速渡船、旅游船和大型液化天然气运输船是今后应用更大功率的 LM2500＋G4 燃气轮机的潜在领域。

(吉桂明 供稿)

has realized a flameless combustion and the reactor has a uniform temperature distribution, the pollutant emission level of exhaust gases is far lower than that set by the applicable national standard. **Key words**: flameless combustion at a normal air temperature, coal-fired boiler being converted to burn gas, high efficiency, reduction of emissions

链条炉横向配风不均匀性的研究= **An Investigation of the Non-uniformity of Transversal Air Distribution for a Chain Grate Stoker** [刊, 汉] / CHANG Bin, YU Ya-hui, JI Jun-jie, et al (Thermal Energy Engineering Research Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —288 ~ 291

The non-uniformity of transversal air distribution in a chain grate stoker can seriously affect the stoker efficiency. To solve this problem, real stoker cold-state tests have been performed of the air supply system of a 20 t/h chain grate stoker in 7 operating regimes. The test results show that the unsatisfactory lateral seal of the grate and air damper deformation are the main causes leading to the non-uniformity of air distribution. With the actually measured data serving as boundary conditions, a numerical simulation was conducted of air flow in a single wind box by employing a $k-\varepsilon$ turbulence model. It has been found that the diffusion-flow pressure drop and a conversion from a kinetic pressure to a static one as well as a turbulence perturbation in the wind box can cause the non-uniformity of transversal air distribution. In the light of the respective merits of large-air-box and small-air-funnel air supply system developed in China and underfeed air supply mode of foreign-made incinerators, proposed was an air supply system incorporating an underfeed large-air-box and small-air-funnel. A numerical simulation of the above two kinds of air supply system indicates that the improved air supply system can effectively enhance the uniformity of transversal air distribution. **Key words**: chain grate stoker, cold state test, transversal air distribution, numerical simulation

燃煤电站锅炉高温腐蚀特征的研究= **A Study of High-temperature Corrosion Characteristics of Coal-fired Utility Boilers** [刊, 汉] / GAO Quan, ZHANG Jun-ying, QIU Ji-hua, et al (National Key Laboratory on Coal Combustion under the Central China University of Science and Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —292 ~ 296

By adopting a variety of microscopic analytic methods, such as metallographic microscope and X-ray diffraction analysis, X-ray fluorescent probe analysis, electronic microscope-energy spectrum analysis by field emission scanning and aperture testing etc., a systematic analysis was conducted for the corrosion products of the water wall of a coal-fired utility boiler. The results of the analysis show that the corrosion products assume a laminar structure with its outer layer being loose and porous and its inner layer rather compact. The corrosion products mainly consist of iron sulfide, iron oxide and a small quantity of silicate. The element distribution regularity of the corrosion products from inside to outside can be given as follows: the content of silicon and aluminium assumes an ascending tendency and that of sulfur and iron a descending tendency. The mineral matter mainly includes iron sulfide and iron oxide generated by corrosion as well as silicon aluminate which originated from fly-ash particles. A comprehensive analysis of the composition and microscopic characteristics shows that the corrosion of the water wall pertains to one of sulfide type. **Key words**: high temperature corrosion, water wall, microscopic structure, X-ray diffraction, coal combustion

基于自抗扰的多变量解耦控制在球磨机的应用= **Application of an Auto-disturbance-rejection-controller-based Multivariable Decoupling Control in Ball Mills** [刊, 汉] / MA Yong-guang, HAO Na, LI Peng-fei, et al (College of Control Science and Engineering under the North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —297 ~ 300

A ball mill-based milling system in a thermal power plant is a typical three-input and three-output system. There is a se-

rious coupling among various variables and it is very difficult to achieve an ideal effect by employing a PID (proportional, integral and differential) control. In the light of these specific features, the authors have applied for the above milling system a new type of control strategy, namely, a combination of auto-disturbance-rejection controller (ADRC) and a multivariable decoupling control. In the meantime, the authors have also made a partial improvement of the ADRC. An auto-disturbance-rejection-based multivariable control system has been designed for a ball-mill milling system and a comparison performed between a reverse-frame normalization design method and Smith forecasting compensation method. The simulation results demonstrate the validity, disturbance rejection and strong robustness of the control algorithm proposed by the authors. Hence, the control strategy under discussion enjoys a very high potential for engineering applications. **Key words**: ball mill, auto-disturbance-rejection controller (ADRC), decoupling control, reverse-frame normalization (RFN), Smith forecasting compensation method

考虑凝汽器压力的火电厂循泵出口阀启闭规律优化＝**Optimization of Open-close Mechanism of Circulation-pump Outlet Valves for a Thermal Power Plant with Condenser Operating Pressure being Considered** [刊, 汉] / YANG Zhi, LIU De-you (College of Water Conservancy and Hydropower Engineering under the Hehai University, Nanjing, China, Post Code: 210098), CHEN Fu-shan (Jiangsu Provincial Engineering Consultancy Center, Nanjing, China, Post Code: 210003)// Journal of Engineering for Thermal Energy &Power. — 2007, 22(3). —301 ~305

When a transient hydraulic change occurs to the circulation water system of a thermal power plant, the condenser may be subjected to a loss of cooling water, leading to an increase of operating pressure of the condenser, and thereby affecting the operating stability and safety of a steam turbine unit. The optimized setting of the open-close mechanism of circulation pump outlet valves can play a definite role in controlling the maximal water loss amount to the condenser. The authors have proposed a method for combining the calculation of a hydraulic transition process with that of the off-design conditions of the condenser to optimize the setting of the valve open-close mechanism. The practical application of the above method for a 300 MW steam turbine unit shows that under the optimized mechanism determined by the method, the minimal flow rate of the condenser has increased from 1.991 m^3/s to 2.271 m^3/s while the highest pressure of the condenser decreased from 22.111 kPa to 16.911 kPa. As a result, the hydraulic safety of the circulation water system has been ensured with a simultaneous consideration of the dynamic characteristics of the condenser during the transient process, thus contributing to a safe and steady operation of the steam turbine unit. **Key words**: thermal power plant, circulation water system, transient hydraulic change, open-close mechanism of valves, condenser operating pressure

船用增压锅炉旋流蒸汽机械喷油器的雾化特性＝**Atomization Characteristics of Swirling Steam-based Mechanical Oil Sprayers for a Supercharged Marine Boiler** [刊, 汉] /WANG Jian-zhi, WU Shao-hua, QIN Yu-kun (College of Energy Science and Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001), WANG Yong-tang (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy &Power. — 2007, 22(3). —306 ~309

By using a LPI-3 diffraction type caliper gage of laser particles and a LE-3 atomizing-angle measuring device an experimental study has been conducted of the above-mentioned oil sprayer for marine use. Identified was the variation relationship between the Sauter mean diameter of atomized oil droplets and sprayed oil quantity on the one hand and its oil pressure on the other. By utilizing the Realizable k-ε model, the turbulent gas flow was simulated followed by a simulation of the droplet movement by using a random orbit model. The deformation and fragmentation of droplets were also simulated by employing the LISA and TAB models. A numerical simulation was performed of the atomization process of the above-mentioned oil sprayer along with an analysis of the effect of the atomized air and oil mass flow rate in the oil sprayer on the atomization characteristics. The simulation results are in comparatively good agreement with the test ones. The research indicates that when the oil spray pressure is above 1.1 MPa, the oil sprayer characteristics comply with the general