文章编号: 1001- 2060(1999) 05- 0340- 03

单相螺旋管圈动态特性研究

(西安交通大学)　黄锦涛　陈听宽

摘　要: 从过程基本方程出发,建立了单相螺旋管圈及垂直管圈的动态特性方程,并经过二次建模,得到了能够直接求解的微分方程组,将理论计算结果与试验曲线做了比较,证明了模型的正确性,所得结果对进一步研究直流锅炉螺旋管圈水冷壁动态特性具有一定的参考意义。

关　键　词: 螺旋管圈; 动态特性; 集总参数; 微分方程组

中图分类号: TK229. 2

符号表

D_1、D_2、D_3	各环节工质流量, kg/s
d_2、d_3	2、3点工质密度, kg/m³;
h_1、h_2、h_3	1、2、3点工质焓, kJ/kg;
V_{12}、V_{23}	12、23管段容积, m³;
l_{12}、l_{23}	12、23管段长度, m;
d_1、d_2	螺旋管及垂直管内径, m;
q_1、q_2	螺旋管及垂直管内壁热负荷, kW/m²;
Q_{12}、Q_{23}	12、23管段工质吸热量, kW;
Q_{y2}、Q_{y3}	12、23管段金属吸热量, kW;
t_{j2}、t_{j3}	2、3点处管壁温度, ℃;
C_j	单位长度金属比热, 0.46 kJ/(kg·℃·m);
K_{12}、K_{23}	传热常数,由稳态值确定;
u_2, u_3	2、3点工质内能, kJ/kg

1　前言

螺旋管圈受热面是变压运行直流锅炉水冷壁的一部分,在锅炉负荷变化时,锅炉水冷壁的动态特性直接影响着锅炉运行的安全性和经济性。变压运行直流锅炉在启动和低负荷运行时,其下辐射区水冷壁(即螺旋管圈部分)通过的工质是单相水,本文就是研究螺旋管圈中工质没有相变时的动态特性。

单相受热管的模型主要有两类: 集总参数模型、分布参数模型,分布参数模型主要针对锅炉的焓-温通道,其基本方程是以时间和长度为自变量的偏微分方程,要得到传递函数必需作一定的简化,最终得到的反映各个动态关系的传递函数都具有超越函数的形式,十分复杂[1]。

为了简化问题,在建立单相受热面数学模型时,最常用的是集总参数模型,集总参数模型求解简单,并且对参量变化较快的环节或过程来说,具有较好的精度[2],而且在求解过程中不必作线性化处理,能较好地反映对象的非线性,适用于全工况仿真。

2　集总参数动态特性模型

变压运行直流锅炉水冷壁,加热管段分为螺旋管段和垂直管段,其示意图见图 1

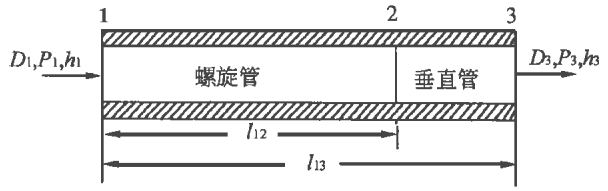


图 1　管段示意图

选用出口参数作为集总参数得到动态特性微分方程:

$$V_{12}\frac{\mathrm{d}d_2}{\mathrm{d}f} = D_1 - D_2 \tag{1}$$

$$V_{12}\frac{\mathrm{d}(d_2u_2)}{\mathrm{d}f} = D_1h_1 - D_2h_2 + Q_{12} \tag{2}$$

$$V_{23}\frac{\mathrm{d}(d_3u_3)}{\mathrm{d}f} = D_2h_2 - D_3h_3 + Q_{23} \tag{3}$$

$$C_jm_jl_{12}\frac{\mathrm{d}t_{j2}}{\mathrm{d}f} = Q_{y2} - Q_{12} \tag{4}$$

$$C_jm_jl_{23}\frac{\mathrm{d}t_{j3}}{\mathrm{d}f} = Q_{y3} - Q_{23} \tag{5}$$

代数方程:

$$Q_{12} = K_{12}l_{12}D_2^{0.8}(t_{j2} - t_2) \tag{6}$$

$$Q_{23} = K_{23}l_{23}D_3^{0.8}(t_{j3} - t_3) \tag{7}$$

$$Q_{y2} = l_{12}q_1\pi d_1 \tag{8}$$

$$Q_{y3} = l_{23}q_2\pi d_2 \tag{9}$$

若忽略温度的变化对水密度的影响,则:

$$\frac{\mathrm{d}d_2}{\mathrm{d}f} = \frac{\partial d_2}{\partial P_2}\frac{\mathrm{d}P_2}{\mathrm{d}f}$$

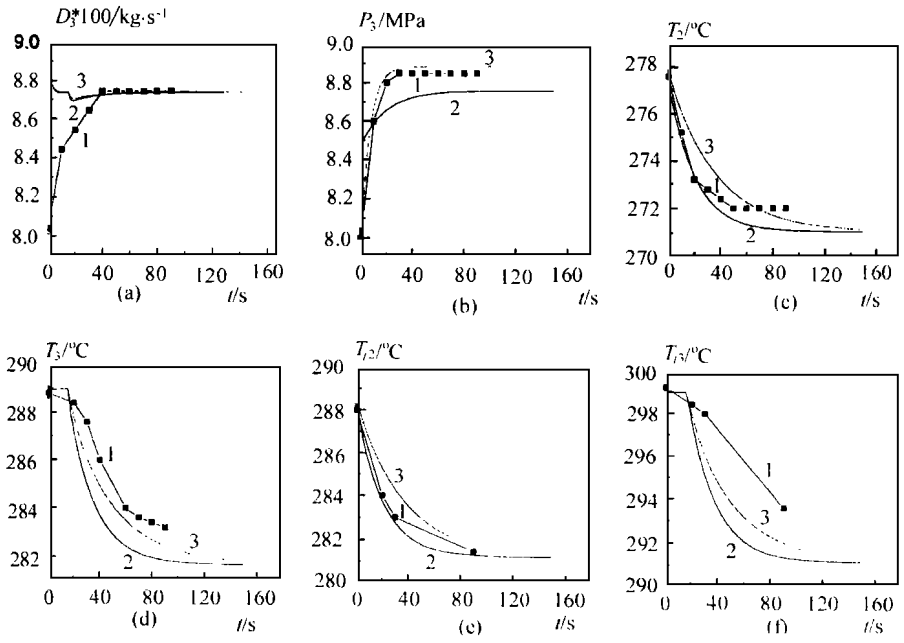
式(1)可变为:

$$V_{12}\frac{\partial d_2}{\partial P_2}\frac{\mathrm{d}P_2}{\mathrm{d}f} = D_1 - D_2$$

令 $C_2 = V_{12}\frac{\partial d_2}{\partial P_2}$,得到:

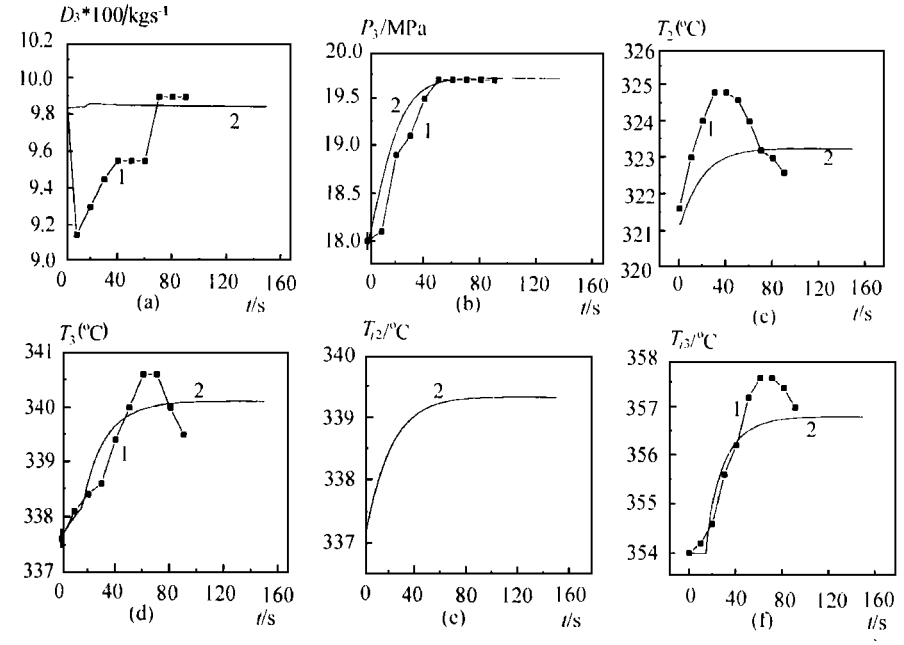
收稿日期: 1998-09-14; 修订日期: 1999-05-19

作者简介: 黄锦涛(1968-),女,讲师,主要从事电厂热力系统动态特性、经济性、节能和诊断方面的研究. 通讯处: 710049　西安交通大学能源与动力工程学院



(a) – 垂直管出口流量　(b) – 垂直管出口压力　(c) – 螺旋管工质出口温度
(d) – 垂直管工质出口温度　(e) – 螺旋管壁温　(f) – 垂直管壁温
曲线 1 – 试验测量值　曲线 2 – 理论计算值　曲线 3 – 压力变化按试验测量值拟合

图 2　入口流量阶跃扰动时各输出响应 (工况 1)



(a) – 垂直管出口流量　(b) – 垂直管出口压力　(c) – 螺旋管工质出口温度
(d) – 垂直管工质出口温度　(e) – 螺旋管壁温　(f) – 垂直管壁温
曲线 1 – 试验测量值　曲线 2 – 理论计算值

图 3　出口压力扰动时各输出响应 (工况 2)

$$\frac{dd_2}{df} = \frac{D_1 - D_2}{C_2} \qquad (10)$$

上述动态特性方程可以化为变系数的常微分方程组[2],应用四阶 Roung-Kutta法求解,可以得到各个变量的值.

3　计算实例及结果

3.1　螺旋管圈动态特性试验简介

为研究螺旋管圈的动态特性,根据 Sulzer公司 600 MW超临界直流锅炉水冷壁的特点,在西安交通大学多相流国家重点实验室高压试验台上进行了螺旋管圈动态特性试验.

试验管段主要由两部分组成,下部螺旋管圈用 H20× 2 mm 1Cr18Ni9Ti不锈钢管制成,总长 19 m,螺旋倾角 14°;上部垂直管圈由两根 H22× 2 mm 1Cr18Ni9Ti不锈钢管制成,长度为 2.8 m,加热管段采用电加热,热负荷均匀.螺旋管圈与垂直管圈之间有混合分配集箱,使得工质混合均匀.

试验针对不同的工况,分别进行了入口流量扰动、入口温度扰动、热负荷扰动情况下,管段输出参数的响应.

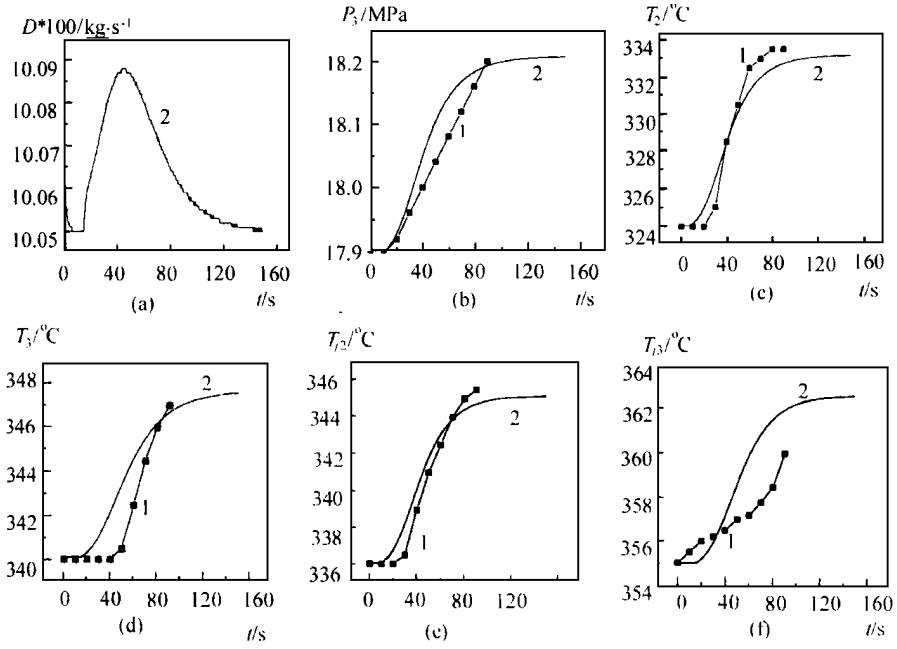
3.2　计算结果

计算根据试验情况选择 4种工况,分别施以不同的扰动量,将计算结果与试验测量到的参数作了比较,结果如图 2~5各工况情况如表 1在求解微分方程组的过程中,将压力 – 流量通道和焓 – 温通道的变量放在一起求解,压力、流量参量的响应比焓温参量的响应快得多,因此会造成非线性耦合[5],影响了计算的准确性,因此本文在计算中,对于工况 1,还采用了只解方程式 (2) ~ (5),计算中用到的压力值根据相应的试验测量值拟合得到,计算结果作于曲线 3

工况 1,入口流量扰动计算值与试验曲线吻合较好,流量增加 8.7% ,工质出口温度降低

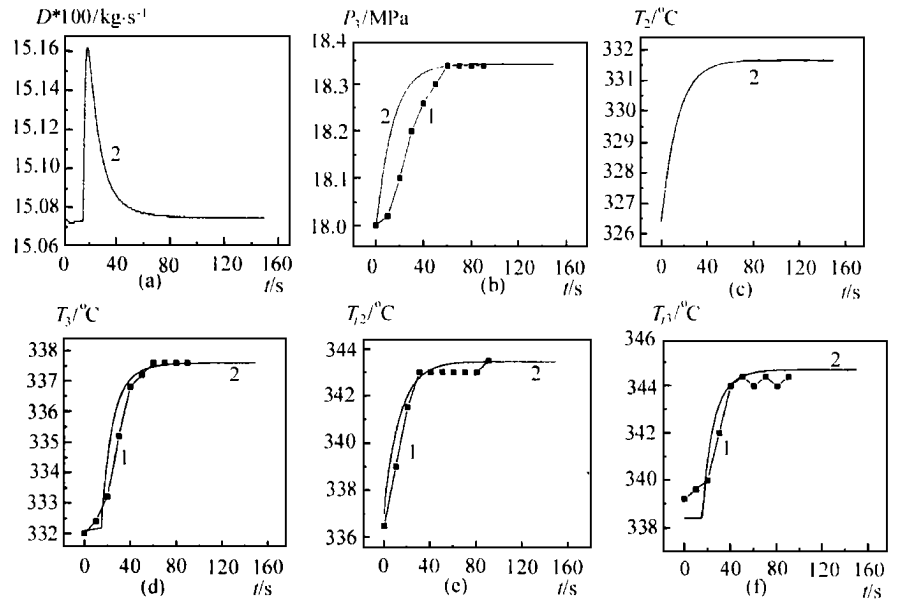
表 1　各工况参数列表

工况	稳态参数	扰动量
1	P_1 = 8.0M Pa, D_1 = 0.1608kg /s	入口流量阶跃增加 8.7%
2	P_1 = 18.0M Pa, D_1 = 0.201kg /s	出口压力增加 10%
3	P_1 = 18.0M Pa, D_1 = 0.201kg /s	入口温度增加 10℃
4	P_1 = 18.0M Pa, D_1 = 0.3015kg /s	热负荷阶跃增加 10%



(a)– 垂直管出口流量 (b)– 垂直管出口压力 (c)– 螺旋管工质出口温度
(d)– 垂直管工质出口温度 (e)– 螺旋管壁温 (f)– 垂直管壁温
曲线 1– 试验测量值 曲线 2– 理论计算值

图 4 进口温度扰动时各输出响应(工况 3)



(a)– 垂直管出口流量 (b)– 垂直管出口压力 (c)– 螺旋管工质出口温度
(d)– 垂直管工质出口温度 (e)– 螺旋管壁温 (f)– 垂直管壁温
曲线 1– 试验测量值 曲线 2– 理论计算值

图 5 热负荷扰动时各输出响应(工况 4)

了 7℃,压力增加,出口工质温度及管壁温度响应理论计算值与试验曲线相比,稳态值略低 1℃多,而且响应快,这说明理论公式中对温度的响应延迟考虑不够。

工况 2,出口压力增加时,工质的出口流量大约有 0.02 kg/s的减少,说明管内工质储量增加,出口工质温度及管壁温度各增加 2℃多,试验曲线显示温度响应有一个先增加又降低的过程,这是由试验中工质进口流量的波动造成的。

工况 3,工质进口温度增加时,出口流量瞬间增加后又回复到初始值,出口压力增加,管内工质储量增加,而出口工质温度及管壁温度也以不同的速度增加。

工况 4,热负荷阶跃增加时,出口流量瞬间增加后又回复到初始值,出口压力增加,而出口工质温度及管壁温度也增加。

4 结论

计算所得到的曲线与试验曲线基本吻合;在试验条件下,加热管段在扰动发生后约 1.5 min即可达到新的稳定状态;出口工质温度及管壁温度的响应延迟理论公式中没有反映出来,因此理论计算得到的温度响应比试验值快,个别工况稳态值也有 1℃左右的误差;总体上,所建立的非线性集总参数模型是能够反映螺旋管段的动态特性。

参考文献

〔1〕 章臣樾主编. 锅炉动态特性及其数学模型. 水利电力出版社, 1987, 6.
〔2〕 丁萃箐编. 换热设备动态特性计算. 水利电力出版社, 1990, 3.
〔3〕 郑建学. 超临界变压运行直流锅炉蒸发受热面动态特性研究:〔博士论文〕西安交通大学, 1996, 01.
〔4〕 西安交通大学,上海锅炉厂. 600 MW超临界变压运行直流锅炉蒸发受热面动态特性研究, 1994, 11.
〔5〕 王广军等. 单相受热面通用动态计算模型. 中国电机工程学报, 1994, 14(4).
〔6〕 范永胜等. 锅炉单相区段的嵌套建模方法. 动力工程, 1995, 15(5).

(渠 源 编辑)

煤粉直接点火燃烧器技术及其进展= **Directly Ignited Pulverized-Coal Burner Technology and Its Development**〔刊,中〕/Li Wenjiao, Yao Qiang, Zhou Junhu, et al (Zhejiang University) //Journal of Engineering for Thermal Energy & Power. - 1999, 14(5). - 327~ 329

In improving the pulverized-coal burners of utility boilers the main focus of attention should be accorded to directly ignited pulverized-coal burners. Based on an integration of direct ignition techniques with combustion stabilization technology the authors have designed a directly ignited pulverized-coal burner. Such burners can be rationally classified into two types: directly ignited pulverized-coal burners without using any fuel oil and directly ignited pulverized-coal ones using only a small quantity of fuel oil. Presented in this paper are the current status of development of these two kinds of burners and their respective drawbacks. It is recommended that main efforts should now be directed to the improvement of directly ignited pulverized-coal burners using no fuel oil. The paper can offer some guidelines during the study of directly ignited pulverized-coal burners for utility boilers. **Key words** pulverized coal, boiler, directly ignited pulverized-coal burner

核态池沸腾中气泡生长和脱离的动力学特征—— 气泡的脱离直径与脱离频率= **Dynamic Characteristics of Bubble Growth and Departure in Nucleate Boiling- Bubble Departure Diameter and Frequency**〔刊,中〕/Yang Chunxin, Wu Yuting, Yuan Xiugan (Beijing University of Astronautics and Aeronautics), Ma Chongfang (Beijing University of Industrial Technology) //Journal of Engineering for Thermal Energy & Power. - 1999, 14(5). - 330~ 333

On the basis of currently available study results this paper introduces a characteristic length scale and time scale to describe the dynamic growth and departure process of bubbles in nucleate boiling. A general correlation between bubble departure diameter and bubble growth time is thereby obtained. Through the use of heat transfer analogous method a general formula has been worked out to calculate the bubble departure diameter. The study results of the present paper are in full agreement with experimental ones provided by other researchers. **Key words** nucleate boiling, bubble, departure diameter, departure frequency

具有煤种和负荷自适应性的新型燃烧器的研究= **The Study of a New Type of Burner with Self- Adaptation to Coal Sort and Load Changes**〔刊,中〕/Chi Zuohe, et al (Zhejiang University) //Journal of Engineering for Thermal Energy & Power. - 1999, 14(5). - 334~ 336

Analyzed are the contradictory mechanisms existing among such factors as intensified ignition, stable combustion during low-load operation, boiler furnace slagging and nozzle burnout, etc. On this basis a self-adaptation principle of burners with respect to coal sort and boiler loads is proposed and some satisfactory application results have been obtained through lab and on-site tests of such boilers. **Key words** pulverized-coal burner, stable combustion at low loads, boiler furnace slagging, control

用饱和核态池沸腾换热机理模型预测加热壁面活化核心密度= **Prediction of the Active Nucleation Density of Heated Wall Surfaces through the Use of a Model Incorporating the Mechanism of Saturated Nucleate Pool Boiling Heat Transfer**〔刊,中〕/Wu Yuting, Yang Chunxin, Yuan Xiugan, et al (Beijing University of Astronautics and Aeronautics) //Journal of Engineering for Thermal Energy & Power. - 1999, 14(5). - 337~ 339

Active nucleation density represents a major parameter in the nucleate boiling process. However, there lacks a unified method for its description. To avoid the difficulty involved in the direct measurement of the active nucleation density, the authors have proposed a prediction method with the help of a model featuring the mechanism of nucleate boiling heat transfer. The measured active nucleate size distribution curves of six types of surfaces are in good agreement with experimental results given by predecessors active in this area of research. This fully demonstrates the reliability of the above-cited model. **Key words** nucleate boiling, active nucleus, size distribution density, heat transfer model

单相螺旋管圈动态特性研究= **A Study of the Dynamic Characteristics of Single-Phase Spiral Tube Coils**

〔刊,中〕/Huang Jintao, Chen Tingkuan (Xi´an Jiaotong University) //Journal of Engineering for Thermal Energy & Power. – 1999, 14(5). – 340~ 342

Based on process basic equations, the authors have set up a dynamic characteristics model for single-phase spiral and vertical tube coils. By way of secondary model building obtained is a group of differential equations, which can be solved directly. The comparison of theoretical results and experimental curves attests to the validity of the above-cited model. The results given in this paper may serve as reference data and information during the further study of the dynamic characteristics of once-through boiler spiral tube-coil water walls. **Key words** spiral tube coil, dynamic characteristics, integrated parameters, differential equation group

应用激光多普勒测速仪研究湍流有旋自由射流= **Research on Turbulent and Swirling Free Jet Stream with the Help of a Laser Doppler Anemometer** 〔刊,中〕/Xiao Kejian (East China University of Science & Technology) //Journal of Engineering for Thermal Energy & Power. – 1999, 14(5). – 343~ 346

An experimental research is conducted of a movable block swirler-produced velocity field and turbulent flow field of a strongly turbulent and swirling free jet stream. The results of study show that this type of swirler is highly conducive to the formation of a central recirculation zone. The average velocity of the jet stream assumes along the axial direction a rapid decrease with the swirling free jet exhibiting an anisotropic turbulence, especially in the recirculation zone. Also discussed in the paper is the transmission direction of the turbulent flow momentum in the flow field. **Key words** turbulent and swirling free jet, laser Doppler anemometer, average velocity distribution, turbulent flow field

汽轮机通流部分故障诊断的热力判据研究= **A Study of the Thermodynamic Criteria for the Failure Analysis of Steam Turbine Flow Path Components** 〔刊,中〕/Yang Yongping, et al (North China Electrical Power University) //Journal of Engineering for Thermal Energy & Power. – 1999, 14(5). – 347~ 349

A systematic analysis and study is conducted of the four categories of thermodynamic criteria (i. e., relative inner efficiency, exergy efficiency, equivalent flow path area and included angle of expansion lines) generally applied to the failure diagnosis of steam turbine flow path components. The mechanism of diagnosis and a method of execution are proposed for each kind of criteria. In addition, taking the 200 MW power generating unit of a power plant as a specific example, the authors have performed a quantitative analysis and computation concerning the above- cited criteria. **Key words** steam turbine, flow path components, failure diagnosis, thermodynamic criteria

膜式壁上稳态热流测量技术的误差分析= **Error Analysis of the Technique for Measuring Steady-State Heat Flux on Membrane Water-walls** 〔刊,中〕/Fang Zhaohong, Liu Xiaolei (Shandong Institute of Civil Engineering), Yue Guanxi (Qinghua University) //Journal of Engineering for Thermal Energy & Power. – 1999, 14(5). – 350~ 352

This paper focuses on a new approach for measuring heat flux density on a solid wall surface by way of solving inverse heat conduction problems. On this basis the authors have by means of a numerical simulation method further discussed from a theoretical perspective the effect of various factors of the heat conduction system itself on the error of this measuring method. Some guidelines concerning the practical use of this method are also presented. **Key words** heat flux measurement, error analysis, number of conditions

用等效热降法确定排汽压力变化对机组经济性的影响= **Determination of the Impact on Machine unit Economic Performance of Exhaust Steam Pressure Variation by an Equivalent Enthalpy Drop Method** 〔刊,中〕/Li Xiuyun, Yan Junjie, et al (Xi´an Jiaotong University) //Journal of Engineering for Thermal Energy & Power. – 1999, 14(5). – 353~ 355

With regard to the impact on machine unit economic performance of exhaust steam pressure variation a new quantitative method, i. e., exhaust pressure equivalent enthalpy drop calculation method, is expounded in this paper. On the basis of steam turbine off-design operating conditions the proposed method determines