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半干式脱硫系统的热量物质衡算模型

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摘　要:开发了主要针对排烟循环流化床烟气脱硫技术,并且适用于其它各类半干法烟气脱硫工艺的热量物质衡算模型和计算软件。采用 1 t/h 锅炉的实烟气脱硫实验台和国内几家典型半干法烟气脱硫系统的运行数据进行了验证,计算准确。该计算模型和软件可用于半干法烟气脱硫工艺的系统设计、运行和工业控制。

关　键　词:半干法烟气脱硫;喷雾干燥;钙基吸收剂;模型

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1　前言

目前技术上比较成熟的 SO_2 控制技术主要集中在烟气脱硫(FGD)方面。烟气脱硫的基本方式一般分为三种:湿式烟气脱硫、干式烟气脱硫和半干法烟气脱硫。国外应用最为普遍的是湿式脱硫技术;其次,是干式和半干式脱硫技术。干式和半干式脱硫技术由于其投资省、占地小、工艺先进、运行费用低等特点倍受国内外研究者青睐,尤其是半干式脱硫技术的开发。尾部增湿活化、喷雾干燥和最新发展起来的排烟循环流化床烟气脱硫技术(CFB－FGD)等均属于半干式烟气脱硫范围。后一种方法由于其先进的技术路线被认为是最具有商业价值和推广前途的方法之一,尤其适合于发展中国家。

2　系统工艺与计算模型

FGD 因其技术上、管理上的成熟性、可操作性和可实施性是目前世界上削减 SO_2 排放的主要手段。无论是湿法工艺还是干法(半干法)工艺,脱硫剂都是 FGD 中的脱硫载体,直接影响整个系统的脱硫效率和运行成本,是 FGD 工艺中的关键因素。钙基吸收剂因其资源丰富、来源广泛、价格便宜,用得最多,约占脱硫吸收剂的 95%左右。典型的半干法工艺是将 $Ca(OH)_2$ 浆液喷入到脱硫反应器中,伴随着浆液蒸发干燥和烟气增湿减温,脱硫剂和烟气中的 SO_2 发生反应生成固态脱硫终产物而达到脱除 SO_2 的目的。通过浆液配制工艺以提高吸收剂活性;脱硫产物再循环或高倍率循环以达到提高吸收剂利用率;降低近绝热饱和温度差和增强塔内传质过程以促进吸收反应的进行等几方面是半干式脱硫工艺的努力方向。无论对于哪一种工艺流程,系统的热平衡计算都是系统设计、运行和控制的基础。因此,建立和开发该计算模型对半干式脱硫技术的工程应用具有非常重要的价值。

2.1　燃烧产物计算

燃烧产物计算需要获得烟气成份、飞灰量和烟气焓温三个方面的数据。该部分计算主要参照锅炉设计的燃烧与热平衡计算。该部分需要重点考虑的是烟气含硫量的计算,煤中的硫主要以有机硫、黄铁矿硫和硫酸盐硫等三种形态存在。只有前两种硫能够燃烧,硫酸盐硫不能燃烧只能计入灰分。由于我国煤的硫酸盐硫含量很少,所以通常以全硫代替可燃硫作燃烧计算。实际上根据灰分的性质和燃烧方法,大约有 70%～90%的硫形成 SO_2 及 SO_3 并转入烟气,因此,在根据钙硫比计算脱硫剂用量时,需要考虑这一因素,适当加以修正。

2.2　物料平衡计算

对于排烟循环流化床烟气脱硫工艺来说,由于采用物料高倍率循环、塔内循环物料浓度是决定循环阻力的关键因素。需要根据阻力变化来控制塔内的物料循环,因此计算塔内物料浓度是非常重要的。主要计算式为式(1)、式(2),循环倍率的计算参照循环流化床的相关资料。

$$G_e = (1 + R)(G_{fh} + G_{tlcw}) \tag{1}$$

G_e－塔内循环物料量(kg/h);R－循环倍率;G_{fh}－入塔飞灰总量(kg/h);G_{tlcw}－脱硫生成物总量(kg/h)。

$$G_{tlcw} = G_{zz} + G_{scw} + G_{wfy} \tag{2}$$

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G_{zz}— 脱硫剂杂质量(kg/h)；G_{scw}— 脱硫反应生成物量(kg/h)；G_{wfy}— 未参加反应的脱硫剂量(kg/h)。

2.3　水量平衡计算

为保证系统获得高的脱硫效率，系统出口烟温必须尽可能接近烟气饱和温度，但是过分接近饱和温度会引起尾部结露，从而影响系统的稳定运行。所以近绝热饱和温度是半干法烟气脱硫系统的关键控制参数，且烟气绝热饱和温度(露点)也是进行系统水量平衡计算的关键参数。烟气露点通常有酸露点和水露点两个概念，在锅炉设计中所说的露点通常是指烟气酸露点，主要是防止烟气中的硫酸蒸汽凝结而引起腐蚀。在半干法烟气脱硫系统中，由于硫酸蒸汽会首先被脱除，且大量实验表明：烟气中 SO_2 的含量高低，对露点变化几乎没有影响，所以本计算模型中的露点主要是指烟气水露点而言，并适当考虑对应的酸露点加以修正。这一点的确定是进行水量平衡计算的关键，水露点的计算如式(3)。系统水量平衡计算见式(4)，具体计算步骤可参见第 3.1 节“计算程序流程”。

$$T_s = \frac{1\,750.286}{8.107\,65 - \log P_{H_2O}} - 235 \qquad (3)$$

T_s— 烟气水露点(℃)；P_{H_2O}— 烟气水蒸气分压力(Pa)

$$G_{H_2Ock} + G_{H_2Ofy} + G_{H_2Owl} = G_{H_2Ork} + G_{H_2Olf} + G_{H_2Ojy} + G_{H_2Owk} \qquad (4)$$

G_{H_2Ock}— 出塔烟气含水量(kg/h)；

G_{H_2Ofy}— 化学反应耗水量(kg/h)；

G_{H_2Owl}— 出塔物料含水量(kg/h)；

G_{H_2Ork}— 入塔烟气含水量(kg/h)；

G_{H_2Ojy}— 入塔浆液含水量(kg/h)；

G_{H_2Owk}— 系统温控喷水量(kg/h)；

G_{H_2Olf}— 脱硫塔漏风含水量(kg/h)。

2.4　热量平衡计算

水量平衡方程和热量平衡方程联立求解是文中计算的核心，根据烟气性质求解烟气放热量；根据热化学反应方程式求解化学反应放热量；根据雾化种类来确定雾化介质的含热量、空气介质吸热量、蒸汽介质放热量；半干法烟气脱硫工艺属于喷水减温增湿过程，入塔水分蒸发吸热，可根据入出口蒸汽焓值和入塔水焓来求取蒸发水所需热量；其它吸热还包括浆液固含物吸热、脱硫塔热损失、漏风吸热等，其具体的热量平衡方程可见式 5。

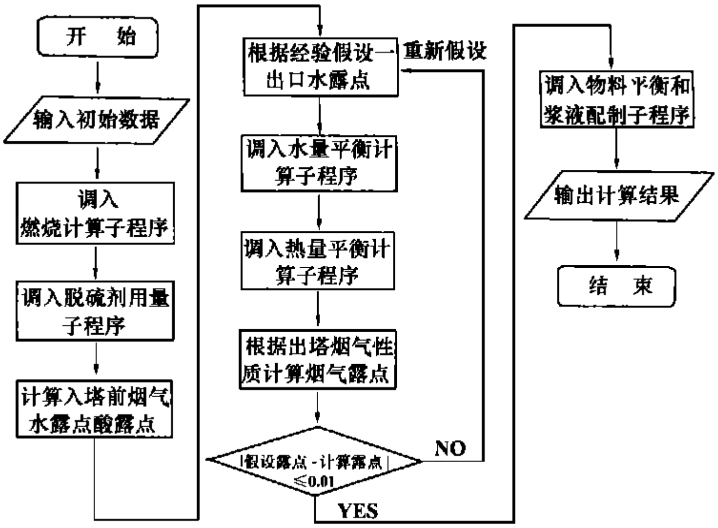
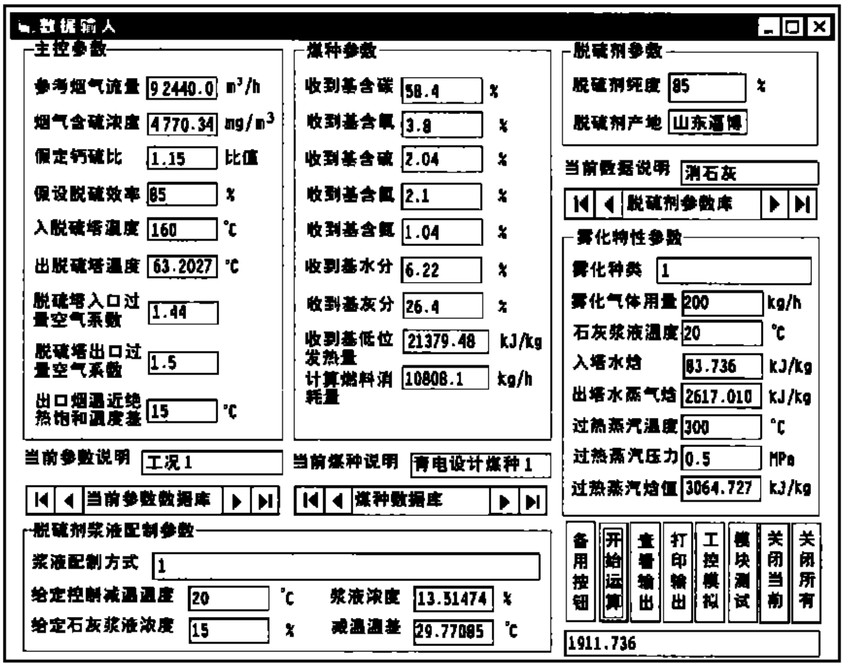


图 1　计算流程图



参考烟气流量 92440.0 m³/h
烟气含硫浓度 4770.34 mg/m³
假定钙硫比 1.15 比值
假设脱硫效率 85 %
入脱硫塔温度 160 ℃
出脱硫塔温度 63.2027 ℃
脱硫塔入口过量空气系数 1.44
脱硫塔出口过量空气系数 1.5
出口烟温近绝热饱和温度差 15 ℃
当前参数说明 工况 1

收到基含碳 58.4 %
收到基含氢 3.8 %
收到基含硫 2.04 %
收到基含氧 2.1 %
收到基含氮 1.04 %
收到基水分 6.22 %
收到基灰分 26.4 %
收到基低位发热量 21379.48 kJ/kg
计算燃料消耗量 10808.1 kg/h
当前煤种说明 青电设计煤种 1

脱硫剂纯度 85 %
脱硫剂产地 山东淄博
当前数据说明 消石灰

雾化种类 1
雾化气体用量 200 kg/h
石灰浆液温度 20 ℃
入塔水焓 83.736 kJ/kg
出塔水蒸气焓 2617.010 kJ/kg
过热蒸汽温度 300 ℃
过热蒸汽压力 0.5 MPa
过热蒸汽焓值 3064.727 kJ/kg

浆液配制方式 1
给定控制减温温度 20 ℃
给定石灰浆液浓度 15 %
浆液浓度 13.51474 %
减温温差 29.77085 ℃

1911.736

注：'*' 为标准状况

图 2　某脱硫系统计算例数据输入窗体

$$Q_{Yfr} + Q_{FYfr} + Q_{ZQfr} = Q_{H_2Oxr} + Q_{GHWxr} + Q_{rs} + Q_{LFxr} + G_{WKxr} \qquad (5)$$

Q_{Yfr}— 塔内烟气放热量(kJ/h)；Q_{FYfr}— 化学反

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应放热量(kJ/h); Q_{ZQfr}— 雾化蒸汽放热量(kJ/h); Q_{H_2Oxr}— 水分蒸发吸热量(kJ/h); Q_{GHWxr}—浆液固含物吸热量(kJ/h); Q_{rs}— 脱硫塔热损(kJ/h); Q_{Lfxr}—脱硫塔漏风吸热量(kJ/h); Q_{WKxr}—雾化空气吸热量(kJ/h)。

3 应用程序开发与计算例

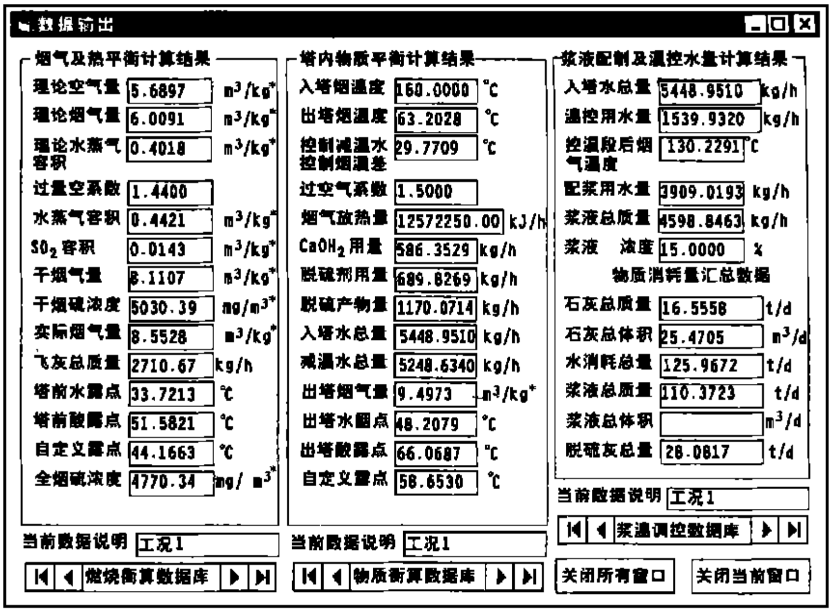
为便于工程应用,根据上述基本计算原理,作者利用 Visual Basic 开发了一套计算软件,并且建立了典型煤种、脱硫剂数据库。对于半干法烟气脱硫工艺来说,控制水平的高低是制约其脱硫效率和系统稳定性的关键因素,因此,本软件充分考虑了系统自动控制需要,可以和工控组态软件组合使用。

3.1 计算程序流程

计算程序流程如图 1 所示。本流程需要根据经验假设一出口水露点数值,系统开始运算,通过水量平衡计算和热量平衡计算求解出口烟气状态。从而可以根据出口烟气性质计算出出口烟气水露点。如果计算出口水露点与假设出口水露点收敛,则进行下一步计算。否则,取此两露点的平均值为新假设值返回计算,直到计算收敛。计算收敛后,程序将根据物料平衡计算求取塔内循环物料浓度、循环倍率等;根据系统各水量数据、温控指标、脱硫剂用量等进一步计算浆液配比、温控水量等数据。

3.2 具体工程计算例

为工程算采用本文计算模型和软件,对某 75 t/h 锅炉半干法烟气脱硫工程进行计算,为工程算例,图中具体数据仅供参考。



烟气及热平衡计算结果

理论空气量	5.6897	m^3/kg^*
理论烟气量	6.0091	m^3/kg^*
理论水蒸气容积	0.4018	m^3/kg^*
过量空系数	1.4400	
水蒸气容积	0.4421	m^3/kg^*
SO_2 容积	0.0143	m^3/kg^*
干烟气量	8.1107	m^3/kg^*
干烟硫浓度	5030.39	mg/m^{3*}
实际烟气量	8.5528	m^3/kg^*
飞灰总质量	2710.67	kg/h
塔前水露点	33.7213	℃
塔前酸露点	51.5821	℃
自定义露点	44.1663	℃
全烟硫浓度	4770.34	mg/m^{3*}

当前数据说明 工况1

塔内物质平衡计算结果

入塔烟温度	160.0000	℃
出塔烟温度	63.2028	℃
控制减温水控制烟温差	29.7709	℃
过空气系数	1.5000	
烟气放热量	12572250.00	kJ/h
$CaOH_2$ 用量	586.3529	kg/h
脱硫剂用量	689.8269	kg/h
脱硫产物量	1170.0714	kg/h
入塔水总量	5448.9510	kg/h
减温水总量	5248.6340	kg/h
出塔烟气量	9.4973	m^3/kg^*
出塔水露点	48.2079	℃
出塔酸露点	66.0687	℃
自定义露点	58.6530	℃

当前数据说明 工况1

浆液配制及温控水量计算结果

入塔水总量	5448.9510	kg/h
温控用水量	1539.9320	kg/h
控温段后烟气温度	130.2291	℃
配浆用水量	3909.0193	kg/h
浆液总质量	4598.8463	kg/h
浆液 浓度	15.0000	%

物质消耗量汇总数据

石灰总质量	16.5558	t/d
石灰总体积	25.4705	m^3/d
水消耗总量	125.9672	t/d
浆液总质量	110.3723	t/d
浆液总体积		m^3/d
脱硫灰总量	28.0817	t/d

当前数据说明 工况1

注: '*' 为标准状况

图 3 某脱硫系统计算例数据输出窗体

4 结论

作者所建立的半干法烟气脱硫工艺热量物质衡算模型与计算软件经过小试验台和国内几家典型半干法烟气脱硫系统的运行数据验证,其计算准确,能够为工程应用提供设计、运行依据,并且是准确实现在线工业控制的基础,可配合工控组态软件使用。

采用本软件已经为 1 t/h 锅炉实烟气半干法脱硫试验台的设计、调试和试验提供依据和参考,并且为某电厂 75 t/h 锅炉的排烟循环流化床脱硫示范工程提供了设计依据。

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Through a simulation calculation of the air-tightness test of a steam turbine vacuum system it is concluded that the vacuum decrease rate is not a single-valued function of the air leakage into the condenser. The vacuum decrease rate can be affected more or less by a multitude of factors. Among these one may list: steam turbine load, cooling water flow rate, inlet temperature of cooling water and condenser tube material, etc. A detailed analysis is peformed of the effect of the above factors on the vacuum decrease rate. The conclusions reached can be of some reference value for a more accurate evaluation of the steam turbine vacuum system. **Key words**: steam turbine, condenser, air-tightness test of a vacuum system

凝汽器喉部蒸汽流动的三维数值模拟＝**Three-dimensional Numerical Simulation of the Steam Flow at a Condenser Throat Section** [刊, 汉] / CUI Guo-min, CAI Zu-hui, LI Mei-ling (Thermal Energy Engineering Research Institute under the Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093) //Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —520～522

With the help of a direct simulation Monte Carlo method incorporating a super-particle model and through a domain-decomposition and mathematical modeling of a steam turbine condenser throat a three-dimensional numerical simulation was conducted of the steam flow at the condenser throat of a specific structure. The simulation of the throat steam flow was undertaken with a focus on the analysis of its flow distribution. As a result, identified were the non-uniformity feature of the throat flow field and the underlying cause of the non-uniform flow field. **Key words**: condenser throat, numerical simulation, direct simulation Monte Carlo method

基于MATLAB的三轴燃气轮机动态仿真模型研究＝**Dynamic Simulation Modeling of a Three-shaft Gas Turbine Based on a Software MATLAB** [刊, 汉] / AO Chenyang, ZHANG Ning, CHEN Hua-qing (Naval Equipment Research Center, Beijing, China, Post Code: 100073) //Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —523～526

Simulation technology represents an effective means for the study of gas turbine performance. With the help of a quasi-nonlinear method set up was the mathematical model of a three-shaft gas turbine. An object-oriented dynamic simulation platform was developed for the three-shaft gas turbine on the basis of a dynamic simulation software MATLAB. The results of the simulation show that the simulation model is correct and rational, featuring simplicity and ease of use. **Key words**: software MATLAB, three-shaft gas turbine, simulation model, object-oriented approach

某型两级涡轮流场数值模拟＝**Numerical Simulation of the Flow Field of a Two-stage Turbine** [刊, 汉] / WU Meng, WANG Song-tao, FENG Guo-tai, WANG Zhong-qi, et al (Energy Science and Engineering Institute under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —527～529

Through the use of a three-dimensional viscous flow calculation program a numerical simulation was performed of a two-stage turbine. The program adopts a Godunov scheme of third-order accuracy with a turbulent flow model being of a B-L algebraic one. During the calculation the effect of a change in specific heat has been taken into consideration. An analysis of the calculation results indicates that there lacks a proper reflection of the matching of gas flow angles. This comes about because the gas turbine was designed and calculated through the use of a stream surface S_2 and single row viscous flow with losses being taken account of. As a result, there emerged a relatively great positive incidence angle in the second stage stator, leading to an ineffective role of adopting a rear loading profile and a failure to achieve an decrease in secondary flow loss. In view of this it is necessary to conduct in the aerodynamic design a calculation of the matching of multi-stage viscous flows. **Key words**: three-dimensional flow, numerical simulation, two-stage turbine

半干式脱硫系统的热量物质衡算模型＝**Calculation Model of Heat and Mass Balance for a Semi-dry Flue Gas Desulfurization System** [刊, 汉] / GAO Ji-hui, WU Shao-hua, Qin Yu-kun (Energy Science and Engineering Institute

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under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), MA Chun-yuan (Shandong Industrial University, Jinan, China, Post Code: 250061)//Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —530～532

A calculation model of heat and mass balance along with relevant software has been developed, which is fit for both flue gas desulfurization in a circulating fluidized bed (CFB-FGD) and various other kinds of semi-dry type flue gas desulfurization systems. The accurate calculation results of the above-mentioned model and software were verified with the help of a 1 t/h boiler flue gas desulfurization test rig and the operating data of several typical semi-dry type flue gas desulfurization systems currently in operation in China. The calculation model and software under discussion may well be employed for the design, operation and industrial control of semi-dry type flue gas desulfurization systems. **Key words**: semi-dry type flue gas desulfurization, spray drying, calcium-based absorbent, model

旋流煤粉多相流动与燃烧一维数学模型及应用＝**A One-dimensional Mathematical Model for Pulverized Coal Multi-phase Swirl Flow and Combustion and Its Applications** [刊,汉]/ CHEN Chun-ming, ZHANG Jian, ZHOU Li-xing (Department of Engineering Mechanics, Tsinghua University, Beijing, China, Post Code: 100084)//Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —533～536

With a view to developing an effective way of numerically simulating the multi-phase swirl flow of pulverized coal and its combustion set up was a one-dimensional mathematical model. Built on the framework of a multi-continuum model, the above-cited mathematical model comprehensively takes into account a gas-solid two-phase swirl flow as well as the pulverized coal combustion and heat transfer. It can be used to simulate in a speedy and effective way the pulverized coal multiphase swirl flow and combustion process, as evidenced by the results of numerical calculation of pulverized coal and gas combustion in the annual duct of a vortex combustor. As a result, obtained were the following main parameters: in-furnace temperature, distribution of pulverized coal flow speed and concentration as well as combustion efficiency, etc. **Key words**: swirl multi-phase flow, pulverized coal combustion, one-dimensional mathematical model, vortex combustor

基于参数化建模的转子有限元剖分＝**Finite-element Meshing of a Turbine Rotor Based on Parametric Modeling** [刊,汉]/ WANG Zhang-qi, AN Li-qiang, PENG Zhen-zhong (Mechanical Engineering Department, North China Electric Power University, Baoding, Hebei Province, China, Post Code: 071003)//Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —537～539

The structural parametrization of a steam turbine rotor was attained through an analysis of its structural features. A method for the parametric modeling of the turbine rotor was put forward, resulting in an enhancement of the inputting efficiency and precision of the rotor initial geometric model. With the use of a Delaunay triangulation method generated by finite element grids a two-dimensional finite-element calculation model has been obtained. The finite-element grids feature a uniform size, a smooth transition in grid refinement and an absence of singular elements. As a result, fully ensured is the precision of finite element-based analytic calculation of the rotor temperature field and thermal stress. **Key words**: steam turbine rotor, parametrization, modeling, meshing

用时间相关法求解定常粘性流场的加速收敛法＝**Accelerating-convergence Approach for Solving a Steady Viscous Flow Field through the Use of a Time-marching Method** [刊,汉]/ ZHANG Yan-ying, WU Meng, SU Jie-xian (Energy Science and Engineering Institute under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), CUI Ming-gen, Department of Mathematics, Harbin Institute of Technology, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy & Power. — 2001, 16(5). —540～542

After a detailed analysis of the CFL number of explicit and implicit scheme it is noted that the key factor influencing the magnitude of CFL lies in a discrete form. To enhance the speed of convergence in solving a steady flow field when a time-marching method is used, it is essential to enlarge the CFL number. Meanwhile, the most direct and effective approach

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