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基于动能法测量乏气送粉煤粉浓度的研究

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摘 要: 通过对空气和煤粉的两相流理论的研究, 分析了乏气送粉锅炉风粉混合过程的基本特征, 从工程应用角度提出若干基本假设, 提出了中储式制粉系统通用的动能法煤粉浓度测量方法。通过对大量采集数据的统计分析, 利用机理与回归相结合的方法, 得出算法模型, 并实时应用于风粉在线监测系统, 简化了对问题的描述, 并保证了所建立的风粉混合过程数学模型得以简化, 为后续的煤粉浓度测量的研究工作打下了扎实的理论基础。结果表明, 风粉混合后动压与混合前一次风(乏气)动压之间的比值能够代表管道内煤粉浓度的大小。此方法适用于中储式制粉系统的煤粉浓度测量。

关 键 词: 煤粉浓度; 动能法; 风粉混合; 乏气送粉
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引 言

对于热风送粉锅炉, 温差法已经基本上较好的解决了锅炉煤粉浓度测量的问题, 而且已在工程中得到了广泛的应用, 但对采用乏气送粉制粉系统的锅炉, 因乏气与粉仓煤粉温度比较接近, 风、粉混合前后温差很小, 不能采用温差法测量煤粉浓度, 国内对于乏气送粉煤粉浓度做了大量研究, 也提出了不少方法[1~3], 如能量法、差压法等, 但均未在工程应用中报道。本文应用气固两相流动基本理论, 分析了乏气送粉锅炉风粉混合过程的基本特征, 如图 1 所示, 从工程应用角度提出若干基本假设, 简化了对问题的描述, 总结出了一套基于动能法测量煤粉浓度的计算模型。经试验证明, 此方法用于测量乏气送粉煤粉浓度是可行的。

1 动能法测量乏气送粉煤粉浓度原理[4~10]

对于中间储仓式乏气制粉系统, 一次风携带在水平方向上没有速度的煤粉运动, 经过一段距离后, 煤粉速度、温度与一次风速度和温度几乎相同, 基本达到平衡。混和前一次风气流静压与风粉混合物静压之间存在差值, 这个差值反映了在不同风量下沿程的各种阻力损失; 混合前气体动压与混合后风粉混合物动压也会存在一定的差值, 这个动压差值主要由加入混合的煤粉所引起, 其大小反映了风粉混合物中煤粉浓度的高低。

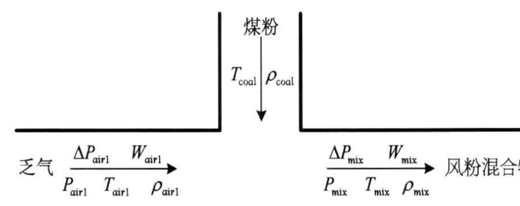

图 1 风粉混合示意图

根据气固两相流的基本理论分析的基础混合过程遵循以下几个基本方程:

状态方程:

$$P_{air1}=R\times\rho_{air1}\times T_{air1} \tag{1}$$

$$P_{air3}=R\times\rho_{air3}\times T_{air3} \tag{2}$$

$$P_{mix}=R\times\rho_{mix}\times T_{mix} \tag{3}$$

式中: P_{air1}、P_{air3}、P_{mix} —风粉混合前空气的压力、风粉混合后空气压力、风粉混合压力, Pa; ρ_{air1}、ρ_{air3}、ρ_{mix} —风粉混合前后空气密度、风粉混合密度, kg/m^3; T_{air1}、T_{air3}、T_{mix} —风粉混合前空气的温度、风粉混合后空气温度、风粉混合物, K; R —气体状态常数, $R=287.05$ J/(kg·K)

连续性方程:

$$\rho_{air1}\cdot W_{air1}=(1-z)\cdot\rho_{air3}\cdot W_{air3} \tag{4}$$

式中: W_{air1} —风粉混合前空气的流动速度, m/s; W_{air3} —风粉混合后空气的流动速度, m/s; z —风粉混合物中固体粒子的体积比。

能量守恒方程:

$$\Delta P_{air1}+P_{air1}-H_{air1}=\Delta P_{mix}+P_{mix}+H_{mix-f}+H_{mix-j} \tag{5}$$

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式中：ΔP_{air1}—混合前空气动能，Pa；ΔP_{mix}—混合后风粉混合物动能，Pa；H_{air1}—风粉混合前空气的沿程阻力损失，Pa；H_{mix-f}—风粉混合后风粉混合物的沿程阻力损失，Pa；H_{mix-j}—风粉混合后风粉混合物的局部阻力损失，Pa。

在风粉混合物测量中，煤粉进入全压测量孔时，孔内静止气体的粘性阻力将阻止煤粉前进，煤粉本身也会与壁面碰撞，使得煤粉速度逐渐减少直至静止，煤粉消耗于阻力的动能传递给气体，转化为气体的动能，使测速装置感受到动压增加。

在马赫数 $Ma<0.2$ 时，可不考虑气体压缩性效应。两相流和单相流一样可以根据伯努里方程得到：

$$\Delta P_{mix}=\frac{1}{2}\rho_{mix}W_{mix}^2 \tag{6}$$

由前面气固两相流的基本理论的可知：

$$\rho_{mix}=\frac{(1+\mu)\cdot\rho_{coal}\cdot\rho_{air3}}{\rho_{coal}+\rho_{air3}\cdot\mu} \tag{7}$$

因为 $\rho_{coal}>>\rho_{air3}$，且通常煤粉浓度 μ 的数量级是 10^{-1}，故式(7)的计算公式可以简化为：

$$\rho_{mix}\approx(1+\mu)\rho_{air3} \tag{8}$$

所以可以得到：

$$W_{mix}=k_2\times k_{mix}\times\sqrt{\frac{2\cdot\Delta P_{mix}}{(1+\mu)\cdot\rho_{air3}}} \tag{9}$$

式中：W_{mix}—风粉混合物流速，m/s；ΔP_{mix}—风粉混合物动压，Pa；ρ_{air3}—风粉混合物中空气的分密度，kg/m^3；k_2—靠背管本身出厂修正系数；k_{mix}—现场流速修正系数。

由于进入管道的空气总容积流量以及假设管道的横截面均不变(如截面有变化，只需要加以换算)，且经过一定距离后，煤粉粒子和气流速度几乎相同，即 $W_{air3}=W_{mix}$，所以根据气体连续性方程可以得到：

$$\rho_{air1}W_{air1}=(1-Z)\rho_{air3}W_{mix} \tag{10}$$

式中：W_{air1}—混合前一次风速，m/s；ρ_{air1}—混合前的空气密度，kg/m^3。

根据靠背管的测量原理得：

$$W_{air1}=k_1\sqrt{\frac{2\Delta P_{air1}}{\rho_{air1}}} \tag{11}$$

式中：ΔP_{air1}—混合前一次风动压差，Pa；k_1—混合前靠背管的综合修正系数，包括靠背管结构工艺以及流量修正系数。

由于 $z=\frac{V_{coal}}{V_{coal}+V_{air3}}\ll 1$，所以将 W_{air1}、W_{mix} 代入式(10)，并且忽略固体粒子体积比 z，经过整理，就可以得到煤粉浓度：

$$\mu=\frac{1}{K}\left[\left(\frac{k_{mix}k_2}{k_{air1}k_1}\right)^2\frac{\Delta P_{mix}}{\Delta P_{air1}}\cdot\frac{\rho_{air3}}{\rho_{air1}}-1\right] \tag{12}$$

式中：K—与煤粉粉尘性质和颗粒度有关的试验系数；ρ_{air1}、ρ_{air3}—混合前、后空气密度，可作近似处理，kg/m^3。则：

$$\rho_{air1}\approx1.205\cdot\frac{293.15}{273.15+t_{air1}} \tag{13}$$

$$\rho_{air3}\approx1.205\cdot\frac{293.15}{273.15+t_{air3}} \tag{14}$$

则煤粉浓度可以表示为：

$$\mu=\frac{1}{K}\left[\left(\frac{k_{mix}k_2}{k_{air}k_1}\right)^2\frac{\Delta P_{mix}}{\Delta P_{air1}}\cdot\frac{273.15+t_{air1}}{273.15+t_{air3}}-1\right] \tag{15}$$

2　基于动能法的风粉浓度测量模型试验

2.1　试验介绍

试验按照如下步骤进行：(1) 首先停止试验管道送粉，并适当加大其它管道送粉量，以保证锅炉负荷；(2) 在停粉送风阶段，通过修正系数校正落粉管前后动压测量值，保证在无粉状态下前后动压一致(落粉管前后风管截面积相同)；(3) 当风粉混合前后温度与动压基本一致后，在给粉机转速可变范围内分段阶跃改变转速，采集相关数据；(4) 当改变转速为某一设定值时，需要一定的稳定时间，以保证风粉混合过程达到平衡，平衡状态以混合后温度、动压基本保持不变为标准。

2.2　试验数据处理[11]

在工业过程中，有些对象的机理可以定性分析，而某些项的系数不能确定，定量的数学关系还明确。对于这一类对象，可以先用机理分析确定模型中的变量，然后用回归方法确定模型参数，这种方法对于处理工业实际对象建模问题不失为一种简单而有效的方法。以最小二乘原理为基础的线性回归技术常用于线性模型的拟合，如表 1 所示。

在数据处理过程中令：

$$M=\frac{\Delta P_{mix}}{\Delta P_{air1}}\cdot\frac{273+t_{air1}}{273+t_{air3}} \tag{16}$$

则，式(15)可以简化为：

$$\mu=\frac{1}{K}\left[\left(\frac{k_{mix}k_2}{k_{air}k_1}\right)^2M-1\right] \tag{17}$$

假设：

$$b_0=-\frac{1}{K} \tag{18}$$

$$b_1=\frac{1}{K}\left(\frac{k_{mix}k_2}{k_{air}k_1}\right)^2 \tag{19}$$

得：

$$u = b_0 + b_1 \cdot M \tag{20}$$

式中：b_0、b_1—回归系数估计值。

表 1 试验数据

转速 / r·min⁻¹	P_{air1} /Pa	T_{air1} /℃	P_{mix} /Pa	T_{mix} /℃	μ /kg·kg⁻¹	$M1=\frac{\Delta P_{mix}}{\Delta P_{air1}}\cdot\frac{273+t_{air1}}{273+t_{air3}}$
100	1 083.484	270.603 7	722.067	259.924 5	0.045 923	0.679 8
200	1 048.516	270.819 8	701.515 3	250.214 3	0.090 5	0.695 4
300	974.018 4	270.896	658.933 4	241.68	0.132	0.714 9
400	923.139	270.878 6	623.828 6	232.019 6	0.183 186	0.727 8
450	897.046 2	271.036 1	601.979 8	225.916 1	0.219 337	0.731 8
500	852.019 4	269.947 1	573.911 2	220.505 3	0.246 331	0.741 1
550	828.322 7	269.744 1	563.390 1	217.172 4	0.267 665	0.753 1
600	807.099 8	268.529 4	553.646 2	210.532 5	0.306 254	0.768 2
650	788.843 3	268.251 8	540.978 9	209.173 7	0.314 536	0.769 8
700	787.009 3	268.378 7	539.545 5	206.205	0.336 155	0.774 5
750	777.946 4	268.644 4	540.415 4	203.068 3	0.361 915	0.790 4
800	760.894 7	268.173 7	542.803 2	199.053 1	0.388 593	0.817 8

运用一元线性回归的方法，根据表 1 的数据以及式(17)，可以估计出 M 与 μ 的关系，如图 2 所示。则：

$$M = 0.357\,8 \cdot \mu + 0.660\,8 \tag{21}$$

煤粉浓度 μ 与 M 的线性相关度 $R = 0.992$。对回归系数显著性进行相关系数检验，在置信水平 α 为 95%，自由度 $f = n - 2 = 6$ 的条件下，相关系数最小值 $r_0(f, \alpha) = 0.705$，而此时 $R > r_0(f, \alpha)$，因此，回归方程有效。

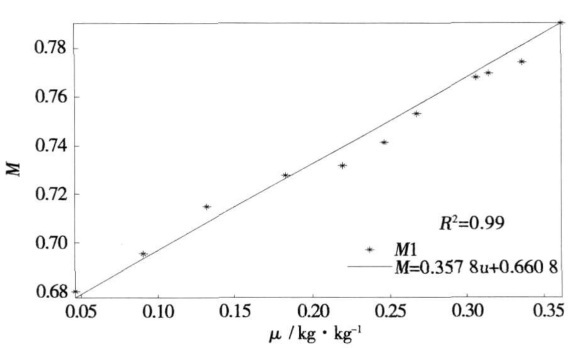

图 2 煤粉浓度 μ 与 M 的关系

2.3 热平衡法与动能法比较

根据回归拟合公式，应用于煤粉浓度的在线测量，图 3 为该方法与热平衡法的比较曲线。本文选取给粉机转速较低、给粉较稳定阶段的数据。从图上可以看出：(1) 动能法与热平衡法测量计算结果基本一致；(2) 热平衡法计算结果曲线光滑，这是由于温度测量信号具有惯性，变化缓慢；(3) 动能法响应较热平衡法快，这是由于压力信号是一个快速变化的信号，在给粉机转速突变，煤粉量增加后，压力信号反应较温度快的结果。当然，由于机理模型的辅助变量中仍有温度参数，故仍有一定的滞后。

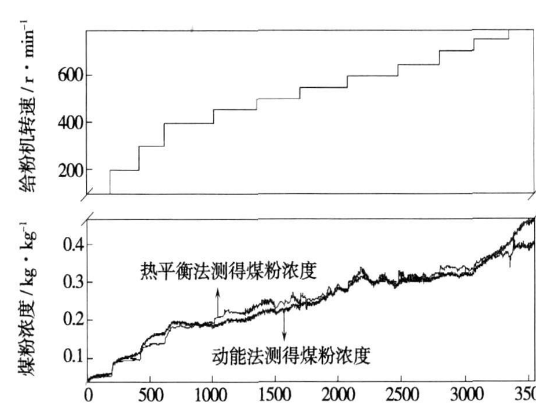

图 3 动能法与热平衡法比较示意图

3 结 论

本文通过对稀疏两相流的理论分析，建立了基于混合前后动压的煤粉浓度测量软测量机理模型，并在现场进行了实验验证，结果表明，风粉混合后动压与混合前一次风(乏气)动压之间的比值能够代表管道内煤粉浓度的大小。但是，由于气固两相流的多态性和复杂性，很难提出一个非常精确的数学模

型，采用风粉混合物作为单相流来考虑，所以空气和煤粉物性参数数据及拟合的公式是混合物物性参数计算的关键，这很难在短时间内面面俱到，是需要一个不断研究、不断发展和不断完善的过程。

动能法能够满足中储式制粉系统风粉浓度测量的要求，目前此方法还需深入研究煤粉浓度和混合前后动能变化的内在关系进行必要的理论分析，使这种方法得到进一步的完善。

在软测量技术方面，软测量模型的维护和校正是其中一个瓶颈；到目前为止，软测量技术还是理论研究多于实际应用，究其原因，很大程度上是缺乏可靠且易于维护的软测量技术软件。研究开放的组件化软件平台，提高实际应用的效率，是软测量工程化今后应该重点考虑的问题。

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（编辑　何静芳）

新技术、新产品

应用接触式经济器提高锅炉的燃料使用效率

据《Энергетика》2007 年 7～8 月号报道，在燃烧天然气的锅炉废气中含有约 15％水蒸气，它们的汽化潜热约为燃料燃烧热量的 15％。

最合理的办法是利用这部分汽化潜热代替低压加热器，用来加热功率为 300 MW 的汽轮机回热系统内的凝水。

对具有接触式经济器的 ГМ－50－14/250 锅炉工作研究结果的分析表明，在 50 t/h 负荷下使天然气消耗量减少 120 Nm^3/h，有害的 NO_x 排放量减少 40％。

在接触式经济器内被加热的水的物理－化学成份实际上没有改变，并且在卫生－技术和化学性质方面符合工业企业和动力工程对它提出的要求。

使用接触式经济器的效果是：废气深度冷却、从废气得到凝水、利用水蒸气冷凝得到的热量制备回热系统的凝水并改进生态性。

（吉桂明　供稿）

5mm, ϕ42×5mm and ϕ38×5mm, analyzed was the influence of mass flow rate and parameters of the working medium on the wall temperature. It has been found that the mass flow rate is a dominant factor for securing a safe operation of the heating surfaces. The temperature difference between the wall surface and working medium decreases with an increase of the mass flow rate. The influence of the tubing structure and the outlet temperature of the working medium on the temperature difference between the wall surface and working medium is not evident, the influence of the tubing structure on the fin temperature, however, is relatively obvious. The pressure only affects the wall temperature to a certain extent. To consider both the safe and economic operation of a boiler at low loads, it is recommended that the design mass flow rate inside the wing wall heating surface should be chosen at a value not lower than 750 $kg/m^2 \cdot s$. The research results can well provide reference for the safe operation of wing wall heating surfaces. **Key words**: circulating fluidized bed (CFB) boiler, wing wall heating surface, metal wall temperature, mass flow rate

旋/直复合流化下循环流化床脱硫塔内的气液分布特性研究＝**A Study of Gas-liquid Distribution Characteristics in a Circulating Fluidized Bed Desulfuration Tower Under a Swirling/straight Composite Fluidization Mode** [刊, 汉] / CUI Lin, MA Chun-yuan, DONG Yong, SONG Zhan-long (Engineering Research Center of Environmental Thermodynamic Process under Education Ministry, College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —367～372

By using a laser-phase Doppler analyzer (PDA) and a dual-loop extraction-type thermocouple, tested was the liquid droplet and gas-phase temperature distribution law in a flue gas circulating fluidized-bed desulfuration tower under a swirling/straight composite fluidization mode. The measurement results show that the liquid droplet distribution in the whole drying process basically assumes a tendency of being more accumulative in the central zone and less so in the side wall zones. When compared with the conventional straight flow fluidization mode with the relative height H/D being greater than 2, the existence of a swirling flow can enhance the liquid droplet drying speed at various points in the tower on the whole. Moreover, the greater the swirling flow rate, the quicker the drying speed. In the nozzle-atomized zone, the flue-gas temperature distribution tends to assume a low value in the middle and a high one at the side walls. When the relative height H/D is lower than 2, the existence of a swirling flow can intensify the above tendency. The presence or absence of swirling flows, however, influences little on the gas phase temperature and distribution when the liquid droplets have been completely dried. From a comprehensive viewpoint, the swirling/straight composite fluidization mode can effectively ameliorate the wall-sticking phenomenon. **Key words**: circulating fluidized bed (CFB), swirling/straight composite fluidization, gas phase temperature distribution, liquid droplet distribution

船用高速齿轮齿根弯曲疲劳强度的计算＝**A Calculation of the Tooth-root Bending Fatigue Strength of a Marine High-speed Gear** [刊, 汉] / LI Xiu-lian (School of Automobile and Traffic Engineering, Jiangsu Technical Normal College, Changzhou, China, Post Code: 213001)// Journal of Engineering for Thermal Energy & Power. — 2009, 24 (3). —373～377

When a ship ploughs the high seas, its hull will produce a hogging or sagging bending deformation due to the action of water buoyancy and ship weight etc., which influences the strength and service life of gears arranged in the hull longitudinal direction. In the light of defects and deficiencies of traditional marine high-speed gears caused by neglecting the inter-tooth friction, centrifugal force and hull deformation during strength calculations, with the driving gear in the involute speed-up gearing unit arranged along the hull longitudinal direction serving as an object of study, derived for the tooth-root bending fatigue was a strength calculation formula with comprehensive consideration of inter-tooth friction, centrifugal force and hull deformation. Calculation cases show that the inter-tooth friction can lead to an increase of the tooth root bending stress by 9.98% with the centrifugal stress accounting for 11.18% of the tooth-root bending permissible stress, while the hull deformation may cause an increase in the tooth-root bending stress by 7.25%. **Key words**: inter-tooth friction, centrifugal force, hull deformation, spur gear, bending fatigue strength

基于动能法测量乏气送粉煤粉浓度的研究＝**A Study of the Kinetic-Energy Method-based Measurement of the Concentration of Pulverized Coal Transported by Exhaust Gas** [刊, 汉] / LI Ji-ming, ZHU Hong, LU Zhen-zhong

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Through a study of air and pulverized coal two-phase flow theory, analyzed were the basic characteristics of an air and pulverized coal mixing process in a pulverized-coal boiler, featuring the transport of pulverized coal by exhaust gas. From the standpoint of engineering applications, several basic assumptions were proposed. A method based on kinetic-energy for measuring pulverized coal concentration was put forward, which has been commonly used in a bin and feeder system. Through a statistical analysis of numerous acquired data and by using a method combining relevant mechanism with regression, a calculation model was obtained and used on a real-time basis in an on-line air and pulverized coal monitoring system, thus simplifying the related problem description, and guaranteeing the simplification of the mathematical model established for air and pulverized coal mixing processes. The forgoing has laid a solid theoretical basis for subsequent research on the measurement of pulverized coal concentration. It has been found that the ratio of the kinetic pressure between two cases, namely, the kinetic pressure after the mixing of the air and pulverized coal and that of the primary air (exhaust gas) prior to the above mixing, can represent the magnitude of pulverized coal concentration in the pipeline. The method under discussion is applicable for measuring pulverized coal concentration in bin and feeder systems. **Key words**: pulverized coal concentration, kinetic energy method, air and pulverized coal mixing, pulverized coal feed by exhaust gas

SO_2气体在微孔 CaO 脱硫剂颗粒内的 Knudsen 扩散＝**Knudsen Diffusion of SO_2 Gas in Microporous CaO Desulfurizer Particles** [刊, 汉] / SHANG Jian-yu, WANG Song-ling, WANG Chun-bo (College of Energy Source and Power Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —382~385

Proceeding from the rarified gas effect and by describing the aerodynamic diffusion mechanism of SO_2 gas molecules in micro-scale pores of CaO desulfurizer particles, the authors have revised the effective diffusion coefficient and established Knudsen diffusion mathematical model, which is based on an aggregate concept. The model was solved mathematically and simplified by using an error function with a functional relationship being established. A simulation analysis shows that when SO_2 gas molecules through the Knudsen diffusion have penetrated into first-stage and second-stage pores, both the fractal porosity and relatively large pore porosity can increase the gas resistance to diffuse inwards, thus enhancing the radial gradient of SO_2 concentration distribution. The research results show that it is feasible to consider only the Knudsen diffusion and ignore gas-solid chemical reaction and other factors during the analysis of gas diffusion in the CaO particles. **Key words**: desulfuration agent, CaO, aggregate, Knudsen diffusion, SO_2, diffusion model

气相温度脉动对煤粉颗粒热解氮化合物释放的影响＝**Influence of Gas-phase Temperature Fluctuations on the Release of Nitrogen Compound in the Pyrolysis of Pulverized Coal Particles**[刊, 汉] / ZHANG Hong-tao, ZHANG Jian (Engineering Mechanics Department, Tsinghua University, Beijing, China, Post Code: 100084)// Journal of Engineering for Thermal Energy & Power. — 2009, 24(3). —386~390

In the presence of gas-phase temperature fluctuations, the transient release process of nitrogenous compound resulting from the pyrolysis of pulverized coal particles was calculated. A functional group (FG-DVC) model was adopted for calculating the transient release rate of nitrogen compound. It has been found that at various time-averaged gas-phase temperatures, the release of pulverized-coal particle nitrogen compound (HCN) in a variety of particle diameters is all influenced by the gas-phase temperature fluctuations. Compared with the case when gas-phase temperature fluctuations have not been taken into account, the release of pulverized coal particle HCN is quickened by such fluctuations. With an increase of the gas-phase temperature fluctuation intensity, the quickening action will be further enhanced. **Key words**: pulverized coal particle, nitrogen compound release, gas-phase temperature fluctuation

压水堆核电机组二回路热力系统矩阵分析法＝**A Matrix Analytic Method for the Second Loop Thermodynamic System of a Pressurized Water Reactor-based Nuclear Power Plant**[刊, 汉] / LIU Qiang, XIN Hong-xiang, CHEN Ling-hai (School of Energy and Power Engineering, Nanjing Engineering College, Nanjing, China, Post Code: 211167),