

# HAT 循环饱和器工质焓计算分析及效率

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**摘要:**饱和器是 HAT 循环中的关键部件,对其性能的认识关系到整个系统的性能分析。运用焓的方法,计算了饱和器工质湿空气和水的焓值,分析了不同参考点的温度和湿度对焓值的影响规律,以及物理焓和化学扩散焓随湿空气温度的变化情况。通过建立饱和器平衡模型,采用了目的焓效率作为饱和器效率。计算结果表明:湿空气焓值随参考点的温度和湿度变化规律为:先减小,直到最低点为零,然后不断增加,焓值始终大于(等于)零,并且与参考点参数差距越大,焓值越大。当湿空气温度增加,物理焓所占比重减少,而化学扩散焓的比重增加,在到达一定温度后,化学焓大于物理焓。

**关键词:**饱和器;湿空气;焓分析;焓效率

**中图分类号:**TK123 **文献标识码:**A

## 符 号 说 明

$\omega$ - 含湿量(质量比)	$\bar{\omega}$ - 含湿量(摩尔比)
$\bar{\omega} = 1.608 \omega$	$T$ - 温度
$P$ - 压力	$h$ - 焓
$s$ - 熵	$e$ - 比焓
$\mu$ - 化学势	$E_{a,o}$ - 出口湿空气焓值
$E_{a,i}$ - 进口湿空气焓值	$E_{w,i}$ - 进口水焓值
$E_{w,o}$ - 出口水焓值	$E_{loss}$ - 饱和器焓损失
$P_{0,w}$ - 代表环境中的水蒸气分压力	
干空气	水蒸气
$R_a = 0.287 \text{ kJ}/(\text{kgK})$	$R_v = 0.461 \text{ kJ}/(\text{kgK})$
$c_{p,a} = 1.003 \text{ kJ}/(\text{kgK})$	$c_{p,v} = 1.872 \text{ kJ}/(\text{kgK})$
下标:	
a - 干空气参数	v - 水蒸气参数
w - 水参数	0 - 环境参数

## 1 引 言

饱和器是 HAT 循环的关键部件,在 HAT 循环中主要起两个作用:增加工质流量,进而增大比功;降低水温,使系统低温余热的回收成为可能,提高整个

循环的效率。因此饱和器在 HAT 循环中占有很重要的地位,对其性能的认识关系到整个系统的性能分析<sup>[1]</sup>。

焓(exergy)又称有效能或可用能,是指在一定参考状态下,能量中可以转化为有用功的部分,它揭示了能量的品位。焓分析是研究能量转化的重要方法,由于具有概念清楚(既反映了能的数量,又反映了能的质量),能够更本质地反映事物的本来面目等优点,并且可以获得科学地对用能实践有指导意义的结果,从而获得了广泛的工程应用<sup>[2]</sup>。本文采用了焓分析的方法对饱和器中的焓计算问题进行了研究。

## 2 饱和器工质焓值计算

### 2.1 湿空气焓值

饱和器是一直接接触式传热传质的部件,不饱和和湿空气与水逆流直接接触,湿空气被加热湿化,水被冷却并部分蒸发。在处理湿空气的时候既存在热量的传递又存在物质的传递(湿度的变化),使得湿空气的焓分析复杂程度增加<sup>[3]</sup>。湿空气是由于干空气和水蒸气组成,因此其焓值可以按照混合气体计算。

通常需要六个变量(外界大气的温度、湿度、压力,湿空气的温度、湿度、压力)来决定湿空气的焓值。其定义式为:

$$e = (\Delta h_a - T_0 \Delta s_a) + \omega (\Delta h_v - T_0 \Delta s_v) + \Delta \omega (h_{0,v} - T_0 s_v) \quad (1)$$

其中:第一项为干空气焓,第二项为水蒸气焓,第三项为通过控制界面进入(或流出)系统的焓量,括弧中的量为在环境介质条件下水的定压定温势(Gibbs 势能)。从式(1)中可以看出,湿空气焓值的计算是和环境大气参数相关联的,并且其零焓参考点的选择也和环境参数相关。但大气空气参数(湿度与温度)不仅是变化的,而且是在很宽的时空范围内变

化,这些变化与气候条件有关。这种差别是不能忽略的,因为过程所利用的湿空气参数都非常接近环境介质,在这种条件下,大气环境参数即使是很小的变化也得考虑,否则将给计算带来严重的误差。因此零焓参考点的正确选择对其分析结果有至关重要的意义,不适当的选择可导致得出不合理的结论<sup>[4]</sup>。

目前提出了许多环境模型来确定参考状态(参考状态是人为定义的一个环境状态,它实质上是一个在一定压力下的无穷大的热源和无穷大的物质源,在此状态下焓值为零),大致可以分为以下3种:(a)取环境大气参数作为焓分析参考点;(b)取环境大气平均气象参数作为焓分析的参考点;(c)取环境温度下的饱和空气状态为焓分析的参考点。各文献选择环境参考点的时候,关键区别是在对水的处理上,若认为液态水是环境中广泛存在的物质,则应选取饱和点为参考点;若认为得到液态水要付代价,则选取环境空气状态为参考点。

在饱和器中,蒸发后冷却的排水可被认为是无代价的,可当作环境中无限大的质量源来考虑,不必考虑其获取所花的热力学代价问题。因而可以直接选取外界大气饱和状态参数点为零焓参考点。

把干空气与水蒸气作为理想气体,根据式(1),就可以推导出湿空气焓值的计算公式<sup>[5]</sup>:

$$e = (c_{p,a} + \omega c_{p,v}) T_0 \left( \frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + (1 + \bar{\omega}) \times R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \left[ (1 + \bar{\omega}) \ln \frac{1 + \bar{\omega}_0}{1 + \bar{\omega}} + \bar{\omega} \ln \frac{\bar{\omega}}{\bar{\omega}_0} \right] \quad (2)$$

式(2)等号右边第一项代表温度不同引起的热焓项;第二项代表压力不同引起的机械焓项(前两项也统称物理焓);最后一项代表由于湿度不同引起的扩散焓项(亦称化学焓)。当式(2)中  $\bar{\omega} = 0$  和  $\omega = 0$  即可得干空气的焓值:

$$e_a = c_{p,a} T_0 \left( \frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right) + R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \ln(1 + \bar{\omega}_0) \quad (3)$$

式(2)与式(3)的差值即为水蒸气的焓值。

### 2.2 饱和器水焓值计算

冷却水焓值的计算同样要涉及到参考状态点的选择。液态水焓值的定义式为:

$$e_w = h_w(T, P) - T_0 s_w(T, P) - \mu_{0,w} \quad (4)$$

其中:  $\mu_{0,w} = h_0(T_0, P_{0,w}) - T_0 s_0(T_0, P_{0,w})$ , 代表了水的化学扩散焓。当水不在系统内循环使用,而是从系统向大气排放时,需要考虑由于水蒸发的水蒸气浓度与环境空气中水蒸气浓度不同而引起的扩散

焓<sup>[6]</sup>。在饱和器使用中,冷却后的水是循环利用,并不排出系统,因此不需要考虑水的扩散焓;在计算湿空气焓值时,已经把外界大气饱和状态作为参考点,这样水的扩散焓也是不用计算的。此时水的焓值可以简单地表示为:

$$e_w = h_w(T, P) - T_0 s_w(T, P) \quad (5)$$

### 2.3 不同参考点对湿空气焓值计算影响

上面已经提到,参考点的选择对湿空气焓值计算有很大影响。在通常情况下,外界大气环境的压力都是1个大气压,而且变化较小,因此在计算湿空气焓值时,认为参考点的压力  $P_0$  固定,取为0.1 MPa。下面只考虑参考点温度和湿度对焓值计算的影响。

#### 2.3.1 温度影响规律

图1显示了湿空气焓值随外界参数点温度的变化情况,大气温度从273~318 K,相对湿度100%。此时的湿空气温度为298 K,相对湿度100%。压力为0.1 MPa。

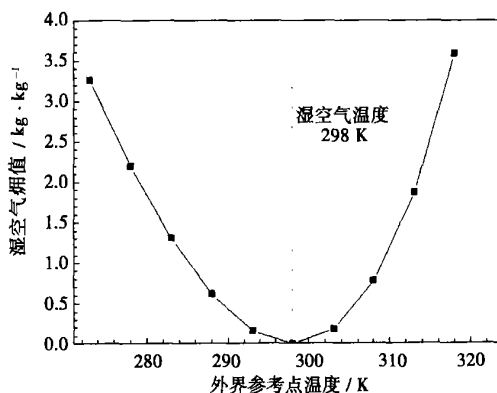


图1 焓值随参考点温度变化规律

从图中可以看出,湿空气焓值先减少,直到最低点为零后(此时外界大气温度与湿空气温度相同),然后开始不断增加,湿空气温度与参考点温度差距越大,焓值越大;并且湿空气温度高于或低于外界参考温度,湿空气的焓值始终大于零(与外界温度相同时等于零)。这也体现了焓本身的含义:焓是可以转化为有用功的那部分能量。当系统温度低于环境温度时,具有的是冷量焓;当系统温度高于环境温度时,具有热量焓,即焓值始终大于(或等于)零。

#### 2.3.2 湿度影响规律

图2显示了湿空气焓值随外界参数点湿度变化规律,大气温度298 K,相对湿度从10%~100%。

此时湿空气温度为 298 K, 相对湿度 50%。压力为 0.1 MPa。

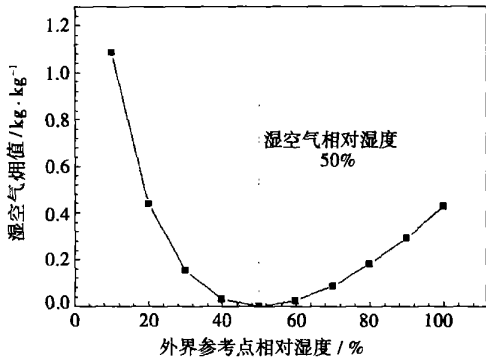


图 2 焓值随参考点湿度变化规律

从图中可见,随着参考点湿度的增加,湿空气焓值的变化规律与温度变化形式相同,都是先减小,后增加。以湿空气湿度为转折点,焓值都大于(等于)零。可以通过湿空气焓的计算公式来解释这一变化规律。

当  $T = T_0, P = P_0$  时,湿空气焓值计算式(2)简化为:

$$e = R_a T_0 \left[ (1 + \bar{\omega}) \ln \frac{1 + \bar{\omega}_0}{1 + \bar{\omega}} + \bar{\omega} \ln \frac{\bar{\omega}}{\bar{\omega}_0} \right] \quad (6)$$

可以证明当  $\bar{\omega}_0 < \bar{\omega}$  时,函数  $e = f(\bar{\omega}_0)$  为减函数;当  $\bar{\omega}_0 > \bar{\omega}$  时,函数为增函数;当  $\bar{\omega}_0 = \bar{\omega}$  时,  $e = 0$ ,即图 2 显示的变化规律。

式(6)是湿空气中扩散焓项的计算公式,表明不论  $\bar{\omega}_0 < \bar{\omega}$  还是  $\bar{\omega}_0 > \bar{\omega}$ ,湿空气的扩散焓总是正的,只要当湿空气的湿度转变到环境空气的湿度时,就能对外提供有用功,而且偏离越大,对外提供的有用功也越大,扩散焓越大。

### 2.4 物理焓和化学扩散焓比重

湿空气的焓由物理焓和化学扩散焓两部分构成。图 3 显示了当湿空气的温度改变时,物理焓和化学焓所占比重的变化规律。此时大气温度为 273 K,相对湿度 100%。湿空气温度从 298 K ~ 343 K,相对湿度 50%。压力为 0.1 MPa。

从图 3 中可以看到,当湿空气温度增加,物理焓所占比重逐渐减少,而化学扩散焓的比重逐渐增加,当湿空气温度大于 312 K 后,化学焓的比重大于物理焓,而且越来越大。这表明当温度增加时,湿度差引起的化学扩散焓逐渐占主要地位,而由温度差

引起的热焓占次要地位(此时由于湿空气与外界大气压力相同,因此机械焓为零)。在同一相对湿度下,温度越高,湿空气的扩散焓越大,吸湿能力越强。

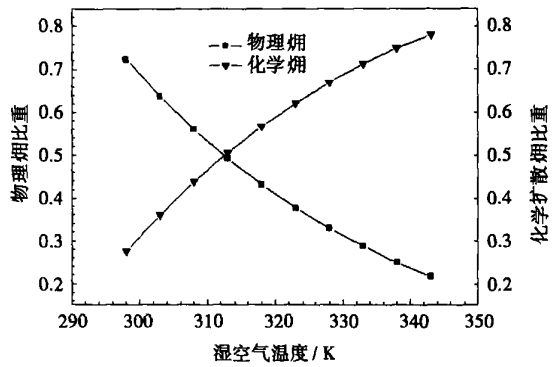


图 3 物理焓和化学焓的比重

## 3 饱和器焓平衡模型和焓效率<sup>[7]</sup>

饱和器内部的实际过程是一个涉及气液两相传热、传质、流动和摩擦阻力等多种因素相互作用的复杂过程<sup>[8]</sup>,在实际分析和计算过程中不可能也不必要将各种因素都考虑进去,感兴趣的只是一些影响能量传递的关键的热力学因素。在通常运行情况下,饱和器内部过程可以认定:(1)气液间传热传质是稳态的;(2)由于饱和器的密闭性和材料的隔热性能比较好,因此对环境的散热损失可以忽略;(3)由于气液间是直接接触,因此造成的流道阻力很小,气体压降可以忽略,同时由于进口水压力引起的水的焓和焓的数值变化也较小,因此内部的传热传质过程可以看作是定压过程;(4)由于进出口气液流速较小,因此由流体的动能引起的焓变化可以忽略。

在饱和器内部水降温冷却,空气被加热加湿,同时考虑到上面的饱和器特性分析之后,就可以建立其焓的简化热力过程模型,图 4 是简化饱和器焓平衡模型示意图:

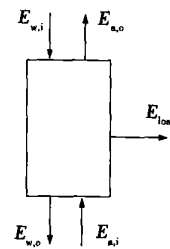


图 4 饱和器焓平衡模型

根据图 4, 可以得出焓平衡方程关系式:

$$(E_{w,i} - E_{w,o}) - (E_{a,o} - E_{a,i}) = E_{loss} \quad (7)$$

针对饱和器的特点并结合常用换热器的性能指标<sup>[2]</sup>, 本文采用了目的焓效率作为焓效率定义, 用于饱和器的焓分析。

目的焓效率 = 收益焓/代价焓

在饱和器内是利用水来加热加湿空气, 同时水降温冷却, 因此收益焓是进口湿空气焓的增加值, 而代价焓为进口水焓的减少值。

$$\eta_{ex} = \frac{E_{a,o} - E_{a,i}}{E_{w,i} - E_{w,o}} = 1 - \frac{E_{loss}}{E_{w,i} - E_{w,o}} \quad (8)$$

采用目的焓效率, 就可以直观地看出以水地焓减少值为基准焓时, 有多少可用能被湿空气所利用, 判断加湿的效果。

在进行具体的工质计算时, 湿空气焓值采用式(2)进行计算; 水焓值可以按照式(5)进行计算, 或者按照文献[9]查表, 并且选择饱和器运行时外界大气的饱和状态点作为湿空气和水焓值零参考点。

## 4 结 论

(1) 湿空气焓由代表温度不同引起的热焓项, 代表压力不同引起的机械焓项(前两项也统称物理焓)和代表由于湿度不同引起的扩散焓项(化学焓)组成。

(2) 湿空气焓值的计算和环境大气参数相关, 并且其零焓参考点的选择也和环境参数相关。

(3) 湿空气焓值随参考点的温度和湿度变化规律为: 先减小, 到最低点为零后, 然后增加。焓值始终大于(或等于)零。

(4) 当湿空气温度增加时, 湿度差引起的化学扩散焓逐渐占主要地位, 而由温度差引起的热焓占次要地位。湿空气的扩散焓越大, 吸湿能力越强。

(5) 根据饱和器焓平衡模型, 得出饱和器的目的焓效率, 可以直观地看出以水的焓减少值为基准焓时, 有多少可用能被湿空气所利用, 判断加湿的效果。

## 参考文献:

- [1] 严家驛, 赵玉珍, 高德敏. 湿空气的比相对湿度和通用焓湿图[J]. 工程热物理学报, 1984, 5(14): 319 - 325.
- [2] 宋之平, 王加璇. 节能原理[M]. 北京: 水利电力出版社, 1985.
- [3] 布罗章斯基 B M. 焓方法及其应用[M]. 王加璇, 译. 北京: 中国电力出版社, 1996.
- [4] 李 震, 江 亿, 刘晓华, 等. 湿空气处理的焓分析[J]. 暖通空调, 2005, 35(1): 97 - 102.
- [5] BEJAN A. Advanced engineering thermodynamics[M]. New York: John Wiley & Sons, 1997.
- [6] 朱明善. 能量系统的焓分析[M]. 北京: 清华大学出版社, 1988.
- [7] 李一兴, 王玉璋, 翁史烈, 等. HAT 循环饱和器性能的焓分析理论研究[J]. 燃气轮机技术, 2005, 18(4): 14 - 17.
- [8] 王玉璋, 李一兴, 翁史烈, 等. 逆流喷雾式饱和器内湿化过程的实验研究[J]. 热能动力工程, 2005, 20(4): 350 - 355.
- [9] 钟史明, 汪孟乐, 范仲元. 具有焓参数的水和水蒸气性质参数手册[M]. 北京: 水利电力出版社, 1989.

(渠 源 编 辑)

## 结构和工艺

# 滑油冷却器结构和生产工艺对其工作效果的影响

据《Теплоэнергетика》2005 年 5 月号报道, 通过基于高精度数值模型完成的数学试验提供了 MB 型滑油冷却器性能研究的结果。

热交换器的结构和生产工艺在很大程度上决定了它的工作效果。借助于减少盘一环隔板的数量、减少在一个行程内由滑油流横断的管排数、保证隔板一罩壳、管子一隔板间隙的最佳尺寸, 能显著节省 MB 型滑油冷却器内用于泵送滑油通过热交换器的电能消耗。

在滑油冷却器结构中, 采用远景的换热增强器能保证相当大地提高热交换器的工作效果。此外, 管间载热体纵向(沿管子)流动是最有利的。

(吉桂明 供稿)

structural features and operating parameters of the nozzle. With compressed air and transformer oil serving as working media an experimental study was conducted of the pressure characteristics in the mixing chamber of the media-atomization nozzle of an internal mixing type. As a result, an experimental relation was obtained between the pressure in the mixing chamber on one hand and the structural and operating parameters on the other hand for this kind of nozzle. This relation can serve as a reference for design and operation engineers. **Key words:** nozzle of internal mixing type, experimental study, pressure characteristics

混输泵半螺旋形吸入室不同含气率下的速度分析= **Analysis of the Velocity Flow-field in the Semi-Volute Suction Chamber of a Multiphase Pump for Different Void Fractions**[刊, 汉] / MA Xi-jin, QIN Xia, NIU Xian-ming (College of Fluid Dynamics and Control under the Lanzhou University of Science & Technology, Lanzhou, China, Post Code: 730050) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). — 186 ~ 188

By using simulation-analysis software CFD (Computational Fluid Dynamics), STAR-CD, a three-dimensional simulation analysis was conducted of the semi-volute suction chamber of a gas-oil multiphase pump for flow fields at different void fractions. The results of the simulation indicate that the variation of flow field velocity is relatively uniform, showing that it is proper to use this kind of semi-volute suction chamber to serve as the suction chamber of a multi-phase pump. However, at a partition tongue location eddies may occur with the phenomenon of gas stagnation emerging, which is related to the magnitude of flow speed and the void fraction of gas. On the basis of analysis results the circular arc radius at the partition tongue location has been augmented and the thickness of the outlet-end partition tongue decreased. The test of a sample machine indicates that there is a significant enhancement of pump efficiency and void fraction, demonstrating the effectiveness of the measures being taken. **Key words:** gas-oil multiphase pump, semi-volute suction chamber, three-dimensional simulation, velocity flow-field analysis

HAT 循环饱和器工质 计算分析及 效率= **Exergy Computational Analysis of the Working Medium of a Saturator and the Exergy Efficiency of the Saturator in a HAT Cycle**[刊, 汉] / LI Yi-xing, WANG Yu-zhang, WENG Shi-lie, et al (Education Ministry Key Laboratory of Power Machinery & Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). — 189 ~ 192

A saturator is the key component of a humid air turbine (HAT) cycle. Knowledge about its performance has a direct bearing on the performance analysis of the system as a whole. The authors have calculated the exergy of the saturator working-medium, i. e. humid air and water and analyzed the law governing the influence of temperature and humidity at difference reference points on exergy as well as the variation of physical exergy and chemical diffusion exergy with a change in humid air temperature. Through the establishment of an exergy equilibrium model for the saturator a target-exergy efficiency has been employed to serve as the exergy efficiency of the saturator. From the calculation results the law governing the variation of humid air exergy magnitude with a change in temperature and humidity at reference points has been identified as follows: the exergy of the humid air first decreases until a minimum value of zero is reached, then there is a continuous rise in value, the exergy magnitude being always greater than (or equal to) zero. Moreover, the greater the difference from the reference-point parameters, the greater will be the exergy magnitude. With an increase in humid air temperature the share taken up by the physical exergy decreases, while that taken up by the chemical diffusion exergy

increases. When a certain temperature has been reached, the chemical diffusion exergy will be greater than the physical one. **Key words:** saturator, humid air, exergy analysis, exergy efficiency

带压缩空气储能的冷热电联产系统的分析= **Exergy Analysis of a Cogeneration System with Compressed-air Energy Storage for the Simultaneous Supply of Electric Power, Heat and Cooling Energy**[刊, 汉] / YIN Jian-guo, FU Qin-sheng, GUO Xiao-kun, et al (College of Energy & Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). — 193 ~ 196

A thermodynamic exergy analysis was performed for a cogeneration system with compressed-air energy storage for the supply of electricity, heat and cooling energy. As a result, obtained were the exergy losses of various major components and the system as a whole as well as the law governing the change of exergy efficiency. The results of the analysis indicate that an increase in adiabatic efficiency of an air turbine can contribute more to an increase in system exergy efficiency than the same increase in efficiency of a compressor. When other parameters have been fixed, there exists an optimum pressure ratio, under which the exergy efficiency of the system can reach a maximum value. A high-temperature heat exchanger represents a major component causing exergy losses in a new type of cogeneration system for the simultaneous production of electricity, heat and cooling energy while the magnitude of circulating water quantity is a major factor influencing the exergy efficiency of the high-temperature heat exchanger. **Key words:** exergy analysis, compressed-air energy storage, air turbine

基于  $T-S$  模型的锅炉蒸汽压力系统在线辨识= **Online Identification of a Boiler Steam Pressure System Based on a T-S Model**[刊, 汉] / HAO Wan-jun, CHAI Qing-xuan, HU Lin-xian, et al (College of Astronautics under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). — 197 ~ 200

A new method for the online identification of the main steam pressure system of a boiler from input-output data is proposed by adopting a T-S (Takagi-Sugeno) model structure. Through the use of a kind of innovative online fuzzy-clustering algorithm and an improved Kalman filter algorithm and by combining a supervised learning method with an unsupervised one online self-adaptation identification by the model has been realized. The model can conduct self-learning during operation and adapt to a very large range of operating conditions as well as the time-variation character of boiler characteristics. The results of simulation have verified the effectiveness of the model-building method put forward by the authors. **Key words:** online identification, fuzzy clustering, Takagi-Sugeno model, Kalman filter, steam pressure

国产 600 MW 机组超临界直流锅炉吹管工艺的研究= **A Study of Steam Purging Techniques for a Chinese-made 600 MW Supercritical Once-through Boiler**[刊, 汉] / GAO Sui-qiang, Huang Lei (Jiangsu Provincial Research Institute of Electric Power Testing, Nanjing, China, Post Code: 210036), WAN Xiao-yan (Nanjing Wiscom Electric Automation Co. Ltd., Nanjing, China, Post Code: 210009) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). — 201 ~ 204

Drawbacks and advantages of two main kinds of steam purging technique currently employed both at home and abroad for boilers, namely, pressure-reduction and stable-pressure methods, are compared and analyzed. On the first Chinese-made