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火力发电厂低压省煤器系统的节能效果研究

任　彦, 赵　宁, 陈晓峰
(华北电力科学研究院有限责任公司, 北京 100045)

摘　要: 针对国内某火力发电厂 300 MW 机组的低压省煤器系统的投运, 进行了节能效果研究。将等效焓降法和热平衡法相结合, 用局部定量计算来替代对整个热力系统的繁琐计算, 对低压省煤器投运后的节能效果进行了计算分析。然后, 对该机组进行了低压省煤器系统投运前后的热耗对比试验, 结果表明, 投运低压省煤器后, 修正后的热耗率降低 45.5 kJ/(kWh), 供电标准煤耗降低 1.649 g/(kWh); 同时证明了上述局部定量计算方法与常规热耗试验计算方法的一致性。

关　键　词: 低压省煤器; 等效焓降法; 热平衡法; 热耗率
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引　言

在电厂中, 锅炉排烟温度高所造成的热损失是锅炉各项热损失中最大的一项, 约占 70% ~ 80% [1]。而在我国, 大批设计温度较高, 运行时间较长的锅炉运行机组, 排烟温度甚至高达 200 ℃左右, 而一般的锅炉的排烟温度在 120 ~ 140 ℃之间[1]。由此可见, 通过技术手段大幅度降低锅炉排烟温度, 利用锅炉排烟余热加热部分凝结水, 从而降低电厂机组热耗和标准煤耗水平是很可观的。在电厂中增设低压省煤器系统即是出于这样一种节能目的而发展起来的[2~4]。

国内某火力发电厂的 300 MW 机组于 2012 年进行了低压省煤器系统的改造。将等效焓降法和热平衡法相结合[5], 用局部定量计算来替代常规的对整个热力系统的繁琐计算, 对低压省煤器投运后的节能效果进行了计算分析。为了比较上述方法与常规热耗试验计算方法的一致性, 又对该机组进行了 300 MW 负荷工况下的低压省煤器系统投运和切除两种方式下的机组热耗对比试验并获得了相应的节能数据。

1　低压省煤器系统

国内某火力发电厂某机组采用的 DG1025/177 - 2 型亚临界、一次中间再热、自然循环、平衡通风、固态排渣、汽包型锅炉; 配东方汽轮机厂制造的 N300—16.7/537/537 型(分缸)亚临界、中间再热、三缸两排汽、凝汽式汽轮机。

2012 年对该机组进行了低压省煤器系统的改造。如图 1 所示, 低压省煤器本体以锅炉对称中心为界, 安装于空预器出口至除尘器入口的四个水平烟道内, 烟道尺寸 5 476 mm × 5 200 mm。低压省煤器管内冷却水与主凝结水成并联布置。其进水取自 2 号低加入口和出口两路, 取水汇合后, 经凝结水升压泵升压后, 进入低压省煤器入口集箱, 吸收烟气热量后汇入出口集箱, 沿回水母管汇入 3 号低加出口母管。为保证低压省煤器进水温度稳定, 在低压省煤器回收母管设计有再循环管, 再循环管汇合到管道升压泵入口。

2　节能效果计算

增设低压省煤器系统后, 实质上其相当于一个提供低品位热源的低加旁路系统。其节能原理为: 通过锅炉排烟余热去加热低加系统的部分凝结水, 从而排挤部分低加系统的抽汽, 被排挤的这部分抽汽视为继续在汽轮机内膨胀做功, 提高系统做功效率。

对于纯凝式汽轮机, 1 kg 新蒸汽的做功就等于它的焓降[5]。而对于回热汽轮机组, 相应 1 kg 汽轮机新蒸汽, 其全部做功量称为它的等效焓降。将所有排挤抽汽所增加发电的功量(记为 ΔW) 称为等效焓降增量, 计算如下:

$$\Delta q = q\left(\frac{\Delta W}{W + \Delta W}\right) \tag{1}$$

式中: Δq—机组热耗率降低值, kJ/(kWh); q—机组热耗率, kJ/(kWh); W—机组负荷, MW; ΔW—低压省煤器系统投运后总增加发电功率, MW, 则:

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作者简介: 任　彦(1986 -), 男, 江西吉安人, 华北电力科学研究院有限责任公司工程师.

$$\Delta W = \sum_{i=5}^{\tau} \Delta W_i - \Delta W_{设备} = \sum_{i=5}^{\tau} \Delta Q_i \times (h_\tau - h_{\tau+1}) - \Delta W_{设备} \quad (2)$$

式中: ΔW_i—汽轮机第 i 级至第 $i+1$ 级因抽汽量减少所增加发电功率,kW; h_τ—汽轮机第 τ 级抽汽焓值,kJ/kg; $\Delta W_{设备}$—引风机,升压泵设备增加用功率,kW; ΔQ_i 为汽轮机第 i 级节省抽汽量,t/h; 而:

$$\Delta Q_7 = \frac{Q_{2低入口}(h_{2低出口} - h_{2低入口})}{h_7 - h_{7疏}} \quad (3)$$

式中: $Q_{2低入口}$—2 号低加入口分支去低压省煤器的流量,t/h; $h_{2低出口}$—2 号低加出口水焓值,kJ/kg; $h_{2低入口}$—2 号低加入口水焓值,kJ/kg; $h_{7疏}$—第 7 级抽汽对应 2 号低加疏水焓值。kJ/kg。而:

$$\Delta Q_6 = \frac{Q_{低省入口}(h_{3低出口} - h_{3低入口})}{h_6 - h_{6疏}} \quad (4)$$

式中: $Q_{低省入口}$—低压省煤器入口凝结水总流量,t/h; $h_{3低出口}$—3 号低加出口水焓值,kJ/kg; $h_{3低入口}$—3 号低加入口水焓值,kJ/kg; $h_{6疏}$—第 6 级抽汽对应 3 号低加疏水焓值,kJ/kg。而:

$$\Delta Q_5 = \frac{Q_{凝}(h_{4低出口} - h_{4低入口})}{h_5 - h_{5疏}} \quad (5)$$

式中: $Q_{凝}$—经过 4 号低加凝结水总流量,t/h; $h_{4低出口}$—4 号低加出口水焓值,kJ/kg; $h_{4低入口}$—4 号低加入口水焓值,kJ/kg; $h_{5疏}$—第 5 级抽汽对应 4 号低加疏水焓值,kJ/kg。

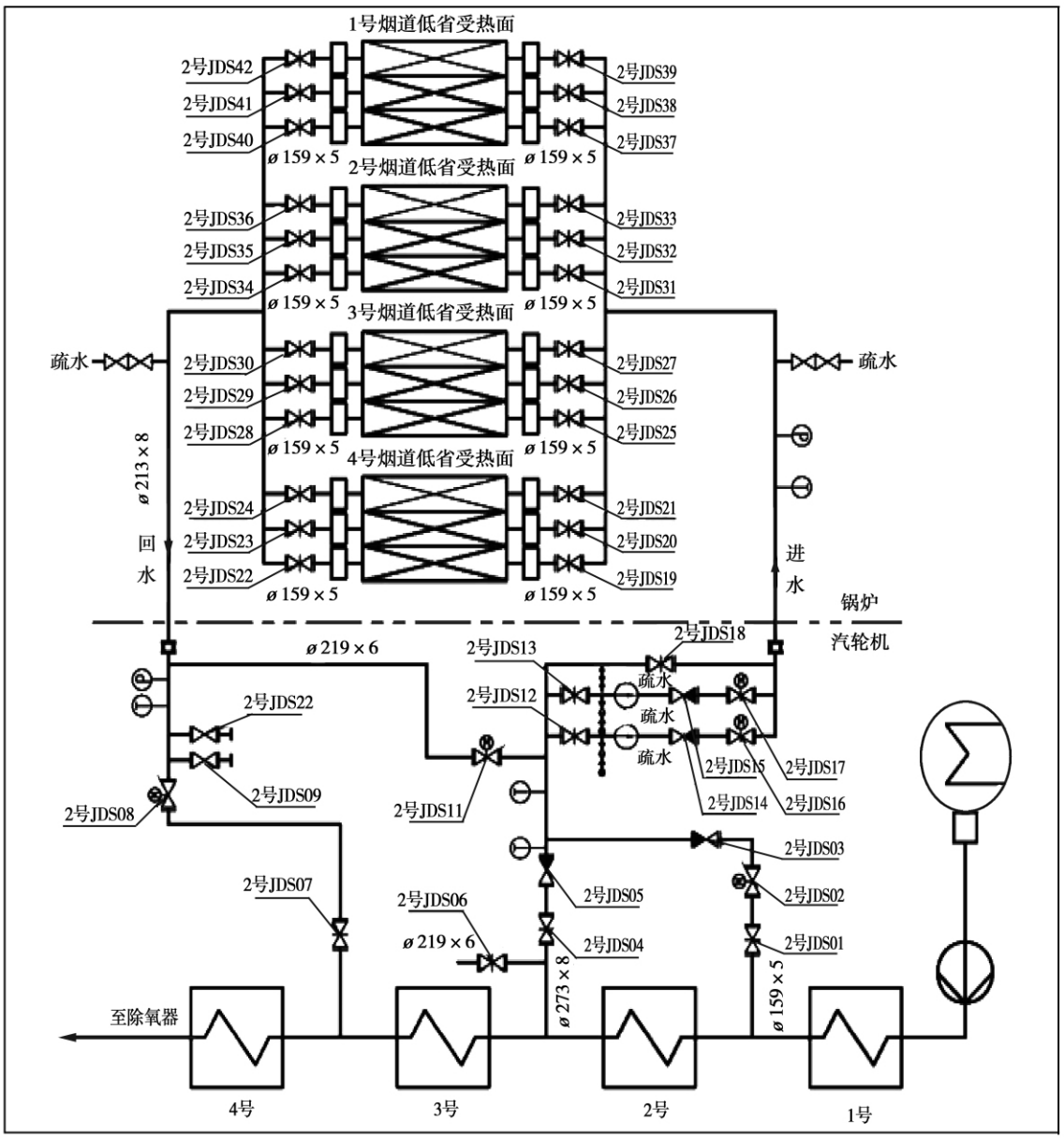

图 1　低压省煤器系统示意图

Fig. 1 Schematic diagram of a low-pressure economizer system

上述低压省煤器系统节能计算方法，是一种结合了等效焓降法和热平衡法的局部定量计算方法，其原始数据来源于第 3 节中提到的，300 MW 负荷工况下，投运低压省煤器时机组的热耗试验，计算结果列于表 1，低压省煤器系统的一些特征数据参见表 2 中的“投运低压省煤器”一列。

由表 1 可见，结合等效焓降法和热平衡法对投运低压省煤器后的热力系统进行局部定量计算，得到机组热耗率降低值为 44.110 kJ/(kWh)。

表 1 等效焓降法和热平衡法相结合的局部定量计算方法的主要指标计算结果

Tab. 1 Results of main indexes calculated by using the partial quantitative calculation method combining the equivalent enthalpy drop method with the heat balance method

指标	数值
5 抽(对应 4 号低加) - 节省抽汽量/t·h^{-1}	-1.15
6 抽(对应 3 号低加) - 节省抽汽量/t·h^{-1}	7.12
7 抽(对应 2 号低加) - 节省抽汽量/t·h^{-1}	8.88
5 抽至 6 抽级 - 因少抽汽后增加功率/kW	-57.77
6 抽至 7 抽级 - 因少抽汽后增加功率/kW	195.28
7 抽至 8 抽级 - 因少抽汽后增加功率/kW	181.64
8 抽至低压缸排汽级 - 因少抽汽后增加功率/kW	1411.45
投运前后总功率增量/MW	1.601
投运前后总热耗率降低值/kJ·(kWh)$^{-1}$	44.110

3 低压省煤器系统投运和切除的机组热耗对比试验

为了验证第 2 节中对低压省煤器经济性计算得到的结果与常规热耗试验计算结果的一致性，并对该机组进行了 300 MW 负荷工况下的低压省煤器系统投运和切除的机组热耗对比试验。

试验分两次进行，每次试验持续 1 h，试验期间参数运行稳定，热力系统按照设计工况运行，热力系统严格隔离并稳定运行。试验一切正常。对采集来的试验原始数据按工况相对稳定的一段连续记录数据进行算术平均值计算，并经大气压力修正。试验中同一参数多重测点的测量值，取算术平均值。各储水装置如除氧器、排汽装置等的水位变化量换算成相应的流量。机组热耗率的计算是通过测得的凝结水流量为基础，对各加热器的物质平衡和热平衡方程推导而得。系统进行第二类修正(参数修正)，采用汽轮机制造厂提供的修正曲线进行修正，修正项目包括：主汽压力、主汽温度、再热蒸汽温度、再热蒸汽压损和背压，试验结果如表 2 所示。

因低压省煤器本体安装于空预器出口至除尘器入口的四个水平烟道内，从而了增加阻力，造成锅炉引风机的出力增大。根据厂家提供的烟道阻力差压 200 Pa，引风机增加电耗为 92.2 kW。而管道泵增加电耗为 37 kW，因此共增加电耗为 129.2 kW，增加厂用电率为 0.043%。

表 2 低压省煤器投运和切除的机组热耗对比试验结果

Tab. 2 Contrast test results of the heat consumption of the unit during the putting-into-operation and cutting-off of low pressure economizers

参数	投运低压省煤器	切除低压省煤器
功率/MW	301.266	300.161
主蒸汽压力/MPa	16.308	16.256
主蒸汽温度/℃	540.356	540.47
高压缸排汽压力/MPa	3.208	3.216
高压缸排汽温度/℃	314.728	315.613
再热蒸汽压力/MPa	2.94	2.952
再热蒸汽温度/℃	541.158	540.349
中压缸排汽压力/MPa	0.735	0.736
中压缸排汽温度/℃	342.1	341.5
低压缸排汽压力/kPa	5.134	5.65
2 号低加入口水温/℃	70.613	71.125
2 号低加出口水温/℃	103.266	102.323
3 号低加出口水温/℃	122.518	122.604
低省入口水压力/MPa	1.336	/
低省入口水温/℃	94.696	/
低省入口水流量/t·h^{-1}	213.934	0
低省出口水温/℃	119.292	/
低省入口烟气温度/℃	142.125	145.666
低省出口烟气温度/℃	122.344	144.978
修正后热耗率/kJ·(kWh)$^{-1}$	8262.1	8307.6
管道泵功率/kW	37	0
引风机增加功率/kW	92.2	0
厂用电率/%	5.243	5.2
供电煤耗/g·(kWh)$^{-1}$	326.556	328.206
试验投运低压省煤器前后供电标准煤耗差值/g·(kWh)$^{-1}$	1.649	

由表 2 数据可知,该机组在 300 MW 负荷工况下,投运低压省煤器后修正后热耗率降低 45.5 kJ/(kWh);供电标准煤耗降低 1.649 g/(kWh);锅炉排烟温度也有将近 20 ℃的降低。由此可见,低压省煤器的投运,可以大幅度降低锅炉排烟温度,利用锅炉排烟余热加热部分凝结水,降低机组的整体热耗和煤耗水平,达到节能的目的。

第 2 节中,结合等效焓降法和热平衡法的局部定量计算方法,获得的投运低压省煤器系统后机组热耗率的降低值为 44.110 kJ/(kWh),与本节中所获得的热耗率降低值 45.5 kJ/(kWh) 偏差极小,约 3.05%。由此可知,结合等效焓降法和热平衡法的局部定量计算方法,对低压省煤器投运后的节能效果计算与常规机组热耗试验计算结果是一致的。

4　结　论

通过计算分析,得到以下两点结论:

(1) 国内某火力发电厂的 300 MW 机组,在额定负荷试验工况下,投运低压省煤器后,机组的锅炉排烟温度降低将近 20 ℃,机组的热耗率和标准煤耗水平有明显降低,分别为 45.5 kJ/(kWh) 和 1.649 g/(kWh),节能效果显著。

(2) 对比结合等效焓降法和热平衡法的局部定量计算方法和常规机组热耗试验计算方法得到的计算结果,即投运低压省煤器前后机组热耗率的差值,发现两种方法计算得到的节能数据是一致的。由此可知,针对电厂低压省煤器系统投运后的节能计算,结合等效焓降法和热平衡法的局部定量计算方法是简捷且有效的。

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(陈　滨　编辑)

新技术、新工艺

船舶推进用燃气轮机技术规范

《Gas Turbine World》2013 年 1 - 2 月刊发布了 2013 年度的船舶推进用燃气轮机技术规范。

介绍了世界各大燃气轮机制造公司的各型船用燃气轮机产品,叙述了各型装置的设计性能规范,包括首台可供应用年份、ISO 条件下的连续功率及其耗油率、ISO 条件下的最大功率及其耗油率、压气机压比、流量、涡轮转速、排气温度,以及燃气轮机的重量和尺寸。

列出了一些本身可直接倒车的船用燃气轮机型号,它们都是乌克兰 Zorya-Mashproekt 研制和生产的。

(吉桂明　摘译)

To the needs to develop various high precision simulation models with a low calculation work load and facilitate to use, established was a three-layer nested model for single-phase heated tubes of a boiler and a study was performed of the heated tubes. The theoretically analytic results based on the Taylor series development method of the transfer functions show that for a disturbance to the enthalpy, flow rate and heat flux at the inlet, the calculation results of the three-layer nested model can approach to those of the distributed parameter model at the third-order, first-order and second-order precision respectively. The simulation results with the superheater of a 600 MW subcritical pressure boiler serving as the object show that the dynamic response of the model in question is in very well agreement with that of the distributed parameter model. Under the three kinds of disturbance, the performance of the three-layer nested model has been improved most conspicuously when compared with that of the two-layer nested model. The three-layer nested model can offer a competitive model choice for simulating real-time full-load simulation and control systems. **Key words:** boiler, single-phase heated tube, lumped parameter, nested structure, model

600 MW **锅炉低压省煤器水侧连接优化选择 = Optimized Choice for the Connection Mode of the Water Side of the Low Pressure Economizer of a** 600 **MW Boiler** [刊, 汉] LU Tai, ZHANG Zi-jian (Northeast University of Electric Power, Jilin, China, Post Code: 132012), ZHANG Su-juan (Chengde Iron and Steel Corporation, Chengde, China, Post Code: 067002) //Journal of Engineering for Thermal Energy & Power. - 2013, 28(4). - 368 ~ 371

According to the test data of a 600 MW power generator unit in a power plant, a cost-effectiveness analysis was performed of the five connection modes of a low pressure economizer in a steam turbine recuperator system by making use of the equivalent enthalpy drop theory. The calculation results show that the parallel connection mode of the low pressure economizer and No. 7 low pressure heater can achieve the best cost-effectiveness, lowering the standard coal consumption rate by 1.79 g/(kW·h). The practical modification effectiveness when analyzed and calculated by using the actual operation data of the low pressure economizer in a power plant after reconstruction was in agreement with the theoretical calculation result. The optimized and calculated results can offer certain guidance for designing and choosing the connection mode of the low pressure economizer of a 600 MW boiler. **Key words:** exhaust gas waste heat, low pressure economizer, equivalent heat drop, connection mode

火力发电厂低压省煤器系统的节能效果研究 = Study of the Energy-saving Effectiveness of a Low Pressure

Economizer System in a Thermal Power Plant [刊,汉] REN Yan,ZHAO Ning,CHEN Xiao-feng (North China Electric Power Science Research Institute Co. Ltd.,Beijing,China,Post Code: 100045) //Journal of Engineering for Thermal Energy & Power. -2013,28(4). -372~375

On the basis of the putting-into-operation of the low pressure economizer system of a 300 MW unit in a thermal power plant in China,studied was its energy-saving effectiveness. First,the authors combined the equivalent enthalpy drop method with the heat balance method and calculated and analyzed the energy-saving effectiveness by using the local quantitative calculation instead of the conventional tedious and complicated calculation of the whole thermal system after the low pressure economizer had been put into operation. Then,they conducted a heat rate contrast test of the unit before and after the low pressure economizer system had been put into operation. The test results show that the corrected heat rate after the economizer had been put into operation decreases by 45.5 kJ/(kWh) while the power supply standard coal consumption becomes lower by 1.649 g/(kWh). In the meantime,it has been proven that the above-mentioned local quantitative calculation method has an identical result to the conventional heat rate test calculation method. **Key words:** low pressure economizer,equivalent enthalpy drop method,heat balance method,heat rate

低负荷下电站锅炉给水前置泵解列运行的必要性分析 = Analysis of the Necessity of Disengaging the Feedwater Booster Pumps of a Utility Boiler at a Low Load [刊,汉] HU Si-ke,HE Xin,CAO Xue-yuan (Northeast University of Electric Power,Jilin,China,Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2013,28(4). -376~380

For the conventional operation mode adopted by boiler feedwater systems with associated electrically-driven main feedwater pumps and booster pumps operating in tandem,presented for the first time was a version to disengage the booster pumps and change to regulate the speed by the main feedwater pumps during stable operation at low loads to meet the requirements for sliding operation of the units. Through determining the characteristic equations of the booster pumps before and after their disengagement in various combination modes and the characteristics of the feedwater pipelines during the sliding pressure operation of the units,the authors put forward a method for seeking solutions to the critical cavitation point of the system at variable loads with corresponding correlation formulae of the