

面向新型电力系统的燃煤发电系统节能方法研究进展

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摘要 “节能优先”是我国经济社会发展坚持的长期战略。“双碳”目标下, 燃煤发电由主体电源向基础保障性和系统调节性电源并重转型, 调峰调频任务剧增. 在此新形势下, 实现调峰调频过程中燃煤发电系统的深度节能, 已成为支撑新型电力系统构建的国家重大急迫需求. 本文从热经济性定量分析方法、稳态工况节能方法及变负荷瞬态过程节能方法三方面梳理了燃煤发电系统节能的发展脉络: 热经济性定量分析方法已由稳态工况拓展至瞬态过程; 稳态工况节能方法包括蒸汽初参数提升、排汽终参数优化、回热系统设计优化、再热参数选择及机炉耦合流程重构等, 且深度调峰工况节能方法正逐步完善; 变负荷瞬态过程节能方法包括主机控制策略优化、辅机瞬态过程调控优化以及电力市场交易机制优化等. 文章最后从超低负荷下燃煤发电节能方法、突破更高参数等级的热力循环优化方法及构建燃煤发电智能化精准调控方法三方面对燃煤发电系统节能方法的未来发展趋势进行了展望, 旨在为构建清洁低碳、安全高效的新型电力系统提供理论支撑与技术参考.

关键词 新型电力系统, 燃煤发电, 节能方法, 稳态工况, 瞬态过程

节能是推动经济社会高质量发展的必由之路. 1980年我国颁布的《关于加强节约能源工作的报告》首次将节能置于国家战略优先地位, 开始了我国节能政策体系的构建历程. 1997年, 我国颁布《中华人民共和国节约能源法》(https://www.mee.gov.cn/ywgz/fgbz/fl/201811/t20181114_673623.shtml), 明确“节能是国家发展经济的一项长远战略方针”. 《2024—2025年节能降碳行动方案》(https://www.gov.cn/zhengce/content/202405/content_6954322.htm)进一步强调“坚持节约优先方针, 完善能源消耗总量和强度调控”. 由此可见, 我国始终将节能优先理念贯穿于国家发展全局, 有力支撑了经济社会高质量发展.

燃煤发电一直是保障我国能源电力安全的“压舱石”, 技术演进始终聚焦能效提升、减排控制与成本效益优化. 我国具有“富煤、贫油、少气”的能源禀赋特

征, 煤炭在一次能源消费中占比超50%(<https://www.stats.gov.cn/sj/ndsj/2024/indexch.htm>), 且半数以上用于燃煤发电. 燃煤发电技术进步可推动电力工业的快速发展. 自1949年以来, 我国电力工业实现历史性突破: 发电装机容量从185万千瓦增长至2024年的33.5亿千瓦(图1), 发电量从仅有43亿千瓦时猛增至2024年的超10万亿千瓦时(https://www.stats.gov.cn/sj/zxfb/202502/t20250228_1958817.html), 稳居世界第一; 燃煤发电参数等级从中温中压发展至超超临界, 单机容量从兆瓦级发展至千兆瓦级, 供电煤耗率从1130 g/(kWh)降低至2024年的302.4 g/(kWh)(图2). 经过数十年攻关, 我国燃煤发电技术已取得了突破性进展, 整体处于世界领先水平.

灵活高效燃煤发电是我国重大需求. 为应对全球气候变化, 2020年9月, 习近平总书记在第七十五届联

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Yan J, Wang Z, Liu M, et al. Research progress on energy-saving methods for coal-fired power systems in the new power system (in Chinese). Chin Sci Bull, 2026, 71: 1596–1608, doi: [10.1360/CSB-2025-5647](https://doi.org/10.1360/CSB-2025-5647)

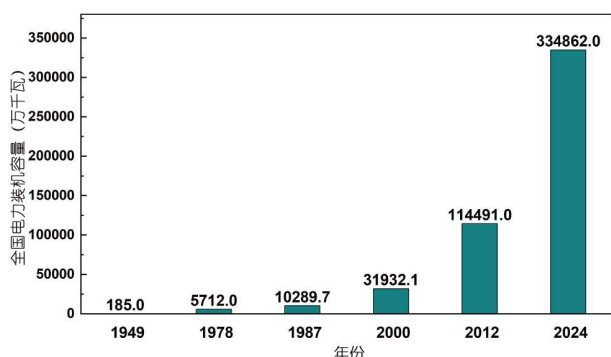


图1 我国电力装机容量

Figure 1 Installed power capacity of China

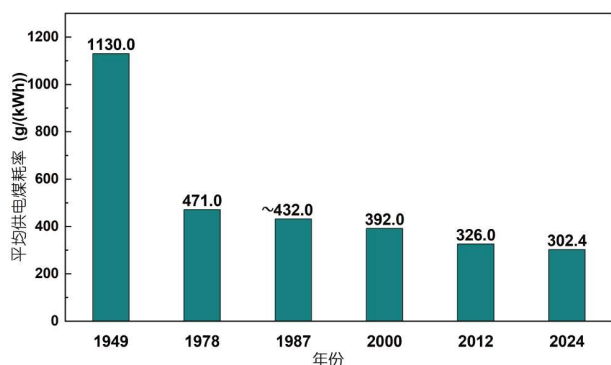


图2 我国火力发电平均供电煤耗率

Figure 2 Average coal consumption rate for thermal power generation in China

联合国大会一般性辩论上提出中国“双碳”目标,在此背景下,我国正加速构建以新能源为主体的新型电力系统,燃煤发电由主体电源向基础保障性和系统调节性电源并重转型。世界各国均重视灵活高效燃煤发电技术,2018年国际能源署发布的《电力系统转型现状》、2020年欧盟的《综合能源系统灵活发电技术白皮书》及2022年我国的《“十四五”现代能源体系规划》(https://www.gov.cn/zhengce/zhengceku/2022-03/23/content_5680759.htm)均明确将“灵活高效发电”纳入重点发展规划。我国在《加快构建新型电力系统行动方案(2024—2027年)》(https://www.gov.cn/zhengce/zhengceku/202408/content_6966863.htm)中进一步强调:“推动煤电机组深度调峰、快速爬坡等高效调节能力进一步提升,更好发挥煤电的电力供应保障作用,促进新能源消纳”。因此,实现燃煤发电灵活高效成为构建新型电力系统的关键。

为支撑燃煤发电系统节能,我国学者开展了大量系统节能方法研究。燃煤发电系统节能研究长期聚焦

于设计工况,主要热经济性定量分析方法包括常规热平衡法、循环函数法、等效热降法、单耗分析法等,采取蒸汽初参数提高、排汽终参数优化、回热系统设计优化、再热参数选择以及机炉耦合流程重构等节能方法,实现燃煤发电系统的高效运行。“双碳”目标下,我国加速构建新型电力系统,燃煤发电系统需频繁参与调峰调频,长期处于变工况及变负荷瞬态过程,燃煤发电系统节能研究由稳态工况拓展至瞬态过程,目前,已建立了包含稳态工况和瞬态过程的热经济性定量分析方法,节能方法由稳态工况的系统优化逐步拓展至瞬态过程的运行调控,从而支撑了燃煤发电系统全工况的高效节能。

为此,本文系统梳理了燃煤发电系统节能的研究进展,重点聚焦于燃煤发电系统热经济性定量分析方法、稳态工况节能方法、变负荷瞬态过程节能方法三方面。

1 燃煤发电系统热经济性定量分析方法研究进展

燃煤发电系统热经济性定量分析方法是系统节能的理论基础,基于热力学第一定律和热力学第二定律,通过量化能量转换与利用环节的损失机制,为热力系统的设计与运行提供科学依据。清华大学^[1]、华北电力大学^[2]、西安交通大学^[3]、浙江大学^[4]、东南大学^[5]、西安热工研究院^[6]、电力建设研究所^[7]等单位在燃煤发电热经济性定量分析方法方面展开了系统深入的研究。

1.1 稳态工况热经济性定量分析方法

常规热平衡法通过热力系统中回热加热器、凝汽器、锅炉的物质与能量平衡计算,确定各加热器抽汽量、凝汽流量、给水流量,进而推导出新蒸汽流量、机组功率及热经济指标。该方法基于热力学第一定律,一直作为其他热经济性定量分析方法的校验基准,是燃煤发电热力系统经济性定量分析的基本方法。

早期因计算资源受限,大量学者通过对热力系统的合理简化,衍生出耗差分析法、循环函数法、等效热降法、单耗分析法等,实现了热经济性指标的快速计算。耗差分析法基于热力学第一定律,通过基准值与实际值的偏差量化能量损失,其核心是确定参数基准值并建立偏差评价体系,适用于运行参数优化与能耗诊断^[8]。循环函数法引入主辅循环思想,通过主循环与

辅助循环的叠加分析热力系统,其核心在于确定各循环流量分配,以量化局部参数变化对热经济性指标的影响,适用于复杂热力系统的结构优化^[9]。等效热降法基于热功转换原理和热力系统拓扑结构,定义了等效热降、抽汽效率等参量,用于分析参数变化对热经济性指标的影响^[10],其核心优势在于计算简捷且具有热力学第二定律的特征,采用局部运算代替整个系统的繁杂计算,经发展完善后,应用范围已拓展至非再热机组^[11]、再热机组^[12]、热电联产机组^[13]、核电机组^[14]等。单耗分析法基于热力学第二定律,将产品能耗分解为理论最低单耗和附加单耗,通过量化各环节附加单耗,获得能耗分布与节能潜力,多用于能耗分布解析与节能潜力挖掘^[15]。

近年来,随着计算机技术飞速发展,计算复杂程度和计算量不再是技术瓶颈。矩阵分析法是在常规热平衡法的基础上发展起来的一种适用于计算机处理的热力系统分析方法,通过矩阵方程联立汽轮机功率与加热器热平衡方程计算热经济性指标,适用于复杂热力系统的热经济性定量分析^[16]。

这些热经济性定量分析方法揭示了燃煤发电系统设计工况下热力参数偏差对热经济性的影响机制,为热力系统设计和优化提供了科学的决策依据。但实际运行时负荷波动、环境变化及设备老化等因素常导致工况偏离设计基准,设计工况的基准值难以反映实际运行特性,且“双碳”目标驱动下,燃煤发电系统长期处于变工况运行。为量化变工况时系统的热经济性,大量学者结合热力学基本原理,通过确定非设计工况下的压力、温度、流量等关键参数,获得了非设计工况下系统的基准状态,实现热经济性分析从设计工况向变工况的拓展^[17,18]。此外,随着人工智能技术的飞速发展,该领域正迈向机理-数据融合的新阶段,国内外学者结合热力学基本原理与大数据分析技术^[19],基于系统历史边界条件建立能耗基准状态模型^[20],提出目标工况高效匹配的定量诊断方法^[21],提升了燃煤发电在稳态变工况时能耗诊断精度。

从常规热平衡法到机理-数据融合的智能方法,热经济性分析方法遵循“原理型-简化型-通用型”的演变逻辑。早期基于热力学第一定律构建原理型方法,奠定了热经济性分析的理论基础;中期受限于计算能力,通过模型简化实现计算便捷性,提升工程实用性;现阶段依托计算机技术与人工智能的突破性发展,形成全工况、多参数、高精度的通用型热经济性定量分析方

法。目前,已经形成了完整的设计工况和稳态变工况热经济性定量分析体系。

1.2 瞬态过程热经济性定量计算方法

瞬态过程是指热力系统从一个稳态工况向另一个稳态工况过渡时,热力状态参数随时间动态演化的非稳态阶段。与能量输入输出平衡的稳态工况相比,瞬态过程中各种热力参数变化的时间尺度不一致,能量转换与损失机制更为复杂。前述稳态热经济性定量分析方法因未考虑时间维度,无法适应瞬态过程热经济性定量分析。鉴于此,需构建引入时间变量的热经济性定量分析方法,以刻画瞬态过程热力参数的时变特征,为实现燃煤发电系统瞬态过程高效运行提供理论支撑。

基于经典热力学原理,多位学者构建了热力系统动态仿真计算模型^[22-25],揭示了瞬态过程中金属蓄热、工质流动延迟及燃烧状态导致的烟损机制^[26],发现瞬态过程能耗明显高于稳态工况能耗,即瞬态过程存在附加能耗^[27,28]。为此,学者建立了瞬态过程能量分析模型,如图3所示,附加能耗由两部分组成:一部分由蓄热变化引起,另一部分是热力参数偏差导致^[29]。由蓄热变化引起的附加能耗称为“蓄热能耗”,其计算方法主要分为两类:一是基于锅炉结构设计数据计算汽包锅炉、直流炉的蓄热系数^[30,31],进而构建蓄热模型;二是采用多状态点的时变热力参数表征系统蓄热时空分布特征^[32]。由热力参数偏差导致的附加能耗为“可控附加能耗”,是瞬态过程的节能潜力,其定量计算方法为:燃煤发电瞬态过程可控附加能耗=瞬态过程能耗-稳态工况

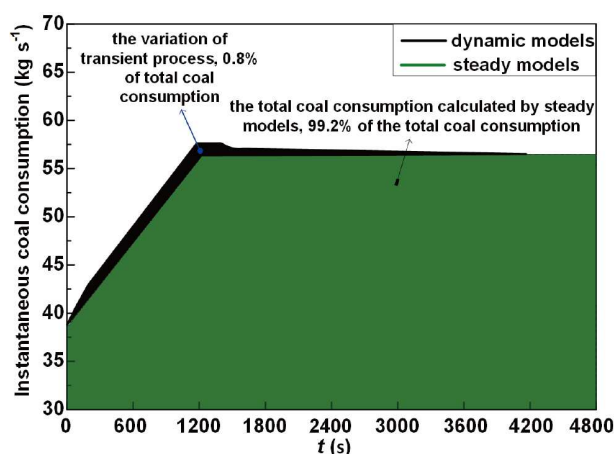


图3 燃煤发电系统瞬态过程节能空间^[29]

Figure 3 Energy consumption saving potential in a coal-fired power plant during transient process^[29]

能耗—蓄热能耗^[29]，这为瞬态过程热经济性计算提供了量化依据。

基于数据驱动的方法，部分学者将热力学原理与实际运行数据深度耦合，实现了耦合大数据的系统节能潜力动态量化评估^[33]。具体包括：采用现场实测数据通过半经验公式量化负荷波动对燃料消耗的影响^[34]；采用极端随机树算法预测动态热耗率偏差，提出变负荷瞬态过程的热耗率修正方法^[35]；结合非稳态能量传递转化和等效热降法建立锅炉-汽轮机系统能耗分析机理框架，通过数据驱动方法实时捕捉变负荷瞬态过程的能耗特性^[36]。上述方法为基于数据驱动的瞬态过程节能优化提供了手段。

2 燃煤发电系统稳态工况节能方法研究进展

燃煤发电技术以朗肯循环为基础，提升其稳态工况热经济性的方法主要包括：蒸汽初参数提高、排汽终参数优化、回热系统设计优化、再热参数选择以及机炉耦合流程重构等。燃煤发电系统能耗随负荷变化，但深度调峰工况下，热经济性影响因素有待进一步明确，节能方法研究处于起步阶段。

2.1 燃煤发电系统稳态工况节能方法

2.1.1 蒸汽初参数提高

提高蒸汽初参数的实质是通过提升工质平均吸热温度从而提高朗肯循环效率。如图4所示，自1975年我国首台亚临界机组投产以来，燃煤发电机组蒸汽初参数等级由亚临界发展至超临界、超超临界。

20世纪70年代，燃煤发电的主蒸汽管道材料以低合金耐热钢为主，参数等级为亚临界，主蒸汽压力约为16.7 MPa，主蒸汽温度多为538℃，供电效率为36%~38%，供电煤耗率为320~340 g/(kWh)^[37]。20世纪80年代，铁素体/马氏体耐热钢研发取得突破，推动燃煤发电参数迈入超临界阶段，主蒸汽压力提升至24 MPa左右、主蒸汽温度提高至566℃，供电效率提升至41%~43%，供电煤耗率降至300 g/(kWh)左右^[37]。21世纪以来，通过采用耐高温合金等材料，燃煤发电参数等级提升至超超临界，主蒸汽压力超过25 MPa，主蒸汽温度提升至580~615℃，供电效率达44%~48%，供电煤耗率降至256~290 g/(kWh)^[38]。

在“十四五”国家重点研发计划引领下，我国燃煤发电正加速向更高参数进一步突破。2023年，中国华能集团积极响应国家重点研发计划“650℃及以上高参数

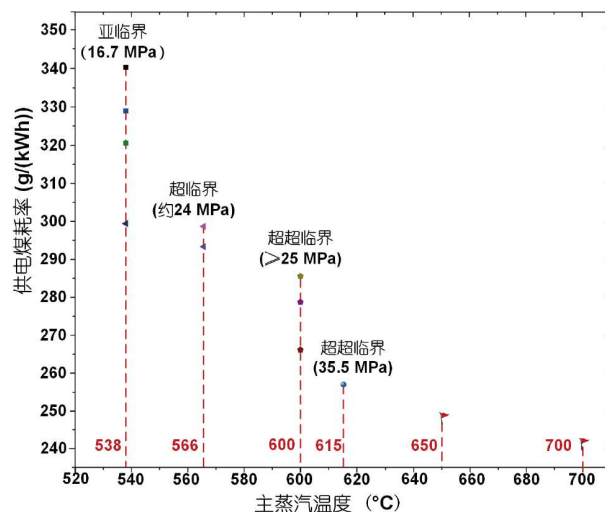


图4 我国燃煤发电参数等级及供电煤耗率

Figure 4 Parameter grades and coal consumption for power generation of coal-fired power plants in China

高效燃煤发电技术及示范(应用示范类)”的专项要求，在华能玉环电厂四期工程中进行应用示范^[39]，该机组主蒸汽温度达到650℃，预期供电效率超48%。2025年，“700℃燃煤发电关键技术”国家重点研发计划项目正式启动，主蒸汽温度达到700℃，预计供电效率将突破50%。

2.1.2 排汽终参数优化

排汽终参数(通常指排汽压力)决定了朗肯循环的平均放热温度，进而影响燃煤发电热效率。排汽终参数优化的核心在于冷端系统优化。冷端系统可分为湿冷与空冷两类。

湿冷机组的冷端优化聚焦于循环水泵最优运行方式，从而获得凝汽器最佳真空。凝汽器真空的确定需基于热经济性分析，构建净功率-耗功曲线以获得最佳真空度，平衡循环水泵电耗与汽轮机功率增量，从而提升发电效率。采用多压凝汽器可实现排汽压力与循环水温的匹配^[40]。而循环水泵运行方式则需结合季节变化，通过台数组合^[41]或变频调速^[42]实现流量-扬程曲线与系统阻力特性的匹配，提高供电效率。

空冷机组分为直接空冷与间接空冷两类。直接空冷系统优化实质上是风机阵列优化问题，通过风机阵列集群运行优化^[43,44]、风机转速调整^[45]等方式平衡散热需求与风机电耗，进而提高机组供电效率。而间接空冷系统分为海勒式和哈蒙式两种，我国燃煤发电多采用哈蒙式间接空冷系统，通过空冷散热器翅片管束设计优化^[46]、百叶窗开度调节^[47]、循环水分布优化^[48]、

循环水泵频率寻优^[49]等方法优化排汽压力,从而提高机组供电效率。

近年来,数字化技术推动冷端优化进入智能阶段。基于大数据分析机器学习算法的智能系统可实现热经济性在线优化指导^[50],为冷端优化开辟新路径。

2.1.3 回热系统设计优化

回热系统通过汽轮机抽汽逐级加热锅炉给水,提高循环平均吸热温度以提升热力循环效率,效率提升效果主要受回热级数、给水温度、焓升分配等参数影响。

随着机组初参数提升与单机容量增加,回热系统设计与优化难度增大。每增加一级回热循环可提升热效率0.3%~0.5%^[51],但提升效果随着回热级数的增加而下降。当前大型燃煤机组回热级数普遍为7~10级,最多达12级,已接近理论极限。通过优化回热系统流程(如外置式蒸汽冷却器^[52])、调整抽汽参数(即焓升分配)^[53,54]等方法可实现回热系统进一步优化节能。

超超临界参数与再热技术的应用导致再热后回热抽汽过热度升高,回热过程的不可逆损失增加。集成回热汽轮机方案^[55,56]是指将部分做过功的蒸汽不经过再热器,直接引入到一台单独的回热汽轮机中,用该回热汽轮机的抽汽和排汽替代原过热度较高的汽轮机主机抽汽,由于回热汽轮机抽汽不经过再热过程,过热度大大降低,有效降低回热系统的不可逆损失,进一步提升了回热系统热经济性。该方案已在1000 MW等级燃煤发电机组取得了应用,发电煤耗率降低了约1.1 g/(kWh)^[57]。

2.1.4 再热参数选择

再热是指将在汽轮机做过功的蒸汽引至再热器升温后,再返回汽轮机继续做功的过程。该方法通过提高循环平均吸热温度提升循环热效率,效果取决于再热温度、压力及级数等。

再热蒸汽温度提升与主蒸汽温度提升对热经济性影响类似^[58],也受耐高温材料的限制。再热蒸汽压力则需基于主蒸汽参数和再热蒸汽温度进行优化匹配,通过热力学计算确定最佳压力区间。增加再热级数可提高循环平均吸热温度进而提高机组效率,一般采用一次再热和二次再热,二次再热通常应用于初参数达到超临界以上的机组,与同参数的一次再热机组相比,二次再热机组发电效率可提升1.0%~2.0%^[51]。2015年,全球首台百万千瓦二次再热超超临界机组(泰州电厂,31 MPa/600°C/610°C/610°C)投运,发电热效率为

47.95%^[59]。

2.1.5 机炉耦合流程重构

机炉耦合流程重构通过优化锅炉和汽轮机的能量传递转换流程实现烟气余热梯级利用,是燃煤发电深度节能的有效手段。典型方法包括烟气余热深度回收和褐煤预干燥等。

排烟热损失是锅炉热损失最大的部分,对能效提升至关重要。早期余热回收以尾部烟道省煤器、空预器为主,通过预热锅炉给水和空气降低排烟温度。近年来,通过汽轮机凝结水加热、锅炉给水加热、锅炉空气预热和烟气放热、回热抽汽放热等过程的深度耦合,构建了旁路烟道^[60]、热风再循环^[61]、联合暖风器^[62,63]等机炉耦合流程重构系统,实现了燃煤发电机组烟气余热深度回收利用的节能。

已探明褐煤保有存量占我国煤炭保有储量的13%左右,褐煤的高含水率导致直接燃褐煤发电机组的锅炉效率普遍低于91%。采用褐煤预干燥方法可提高入炉煤热值以提升机组热效率,按热源类型分为蒸汽预干燥与烟气预干燥两类。蒸汽预干燥以汽轮机抽汽为干燥热源,设计工况节能潜力可达2.19%^[64],但机组变工况时节能潜力衰减快,当机组负荷降至50%左右时,系统节能潜力趋于0;烟气预干燥以锅炉烟气为干燥热源,设计工况节能潜力较小,为1.51%^[65],但系统节能潜力随负荷变化的幅度较小。部分学者提出了烟气-蒸汽复合干燥^[66,67]、热泵干燥^[68]及太阳能干燥^[69]等褐煤预干燥方案,旨在进一步提升褐煤预干燥系统的全工况热经济性。

2.2 燃煤发电系统深度调峰工况节能方法

随着新能源并网比例不断提升,燃煤发电系统需参与深度调峰(负荷率<30%)。深度调峰工况下,系统运行特性发生剧烈变化,供电煤耗率显著上升,且面临锅炉火焰稳定性下降、汽轮机通流效率劣化、辅机效率衰减及工质外排路径复杂等设备安全风险。

如图5所示,某660 MW燃煤发电系统的负荷由100%降低至30%、20%时,热效率由41.2%分别降低至32.66%、23.55%^[70],深度调峰工况下系统的供电热效率显著下降。目前研究从设备安全与能效协同提升角度探索节能方法:锅炉侧通过燃烧精细化调整^[71,72]实现稳燃与效率双提升;汽轮机侧通过通流部分改造^[73]提升效率并降低级间漏汽引发的应力集中;辅机侧采用变频调速技术降低厂用电率并避免电机频繁启停导

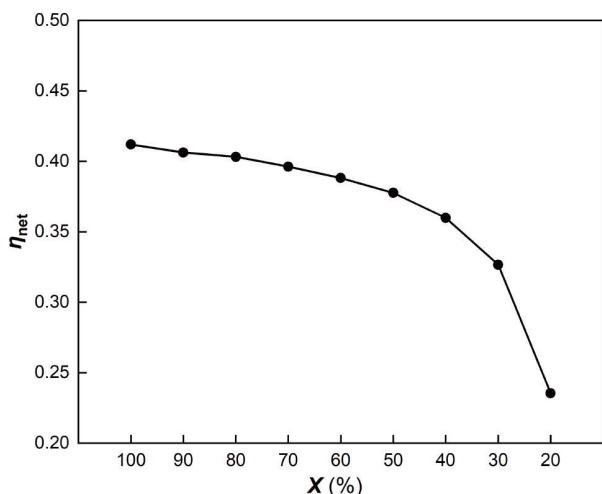


图5 某660 MW燃煤发电系统变工况供电效率特性^[70]

Figure 5 Net energy efficiency characteristics of a 660 MW coal-fired power plant under off-design conditions^[70]

致的机械冲击。此外,当燃煤发电系统受锅炉稳燃负荷限制无法满足深度调峰需求时,耦合外部储能设备可进一步降低输出功率。在系统设计层面,采用构型优化^[74,75]、介质筛选^[76,77]等方法提升系统热经济性;在运行调控层面,通过运行参数优化^[78]、储放热策略优化^[79,80]提升系统热经济性。总体上看,目前尚未形成深度调峰工况下完备的节能方法体系。

3 燃煤发电系统变负荷瞬态过程节能方法研究进展

传统燃煤发电系统控制策略以“稳定运行”为核心目标,随着燃煤发电系统长时间处于变负荷瞬态过程,控制策略需考虑节能需求,以实现变负荷瞬态过程深度节能。燃煤发电系统的变负荷瞬态过程涉及一次调频、二次调频及三次调频。其中一次调频应对随机小负荷波动,属于秒级响应;二次调频应对较大负荷变化,属于分钟级响应;三次调频是多个燃煤发电系统间的负荷分配,属于小时级响应^[81]。燃煤发电变负荷瞬态过程节能方法分为主机控制策略优化、辅机瞬态过程调控优化以及电力市场交易机制优化。

主机控制策略优化聚焦机炉协调控制,分为基于热力学分析的控制策略优化与大数据驱动的控制参数优化两类。基于热力学分析的控制策略优化实质是通过主动调控系统蓄热实现系统节能,具体有两种实施路径:其一是定量计算锅炉汽水系统、凝结水系统和热网系统的蓄热^[82,83],分析不同类型蓄热的动态响应

特性,提出应对一次调频的快速高效控制手段与应对二次调频的以指令分解为基础的燃煤机组前馈-反馈综合协调控制方案^[84,85],降低瞬态过程能耗;其二是将蓄热时空状态作为前馈信号引入风-煤-水控制逻辑(图6)^[86],协同动态调控风、煤、水等多物质流,通过热力学状态感知与动态调控^[87],将传统“被动响应”模式转化为“主动调控”模式,以系统内部蓄热有序利用^[88]为准则提出一次调频与二次调频控制策略优化方法,降低瞬态过程能耗。大数据驱动的控制参数优化则融合深度学习与强化学习技术,结合模型预测控制、模糊控制、自适应控制等先进控制方法^[89-91],以瞬态过程焓损最小化为目标进行参数调控,使系统瞬态过程焓损显著下降^[92]。

辅机瞬态过程调控优化是瞬态过程节能的关键环节,瞬态过程需考虑时间尺度,匹配动态响应特性和辅机系统的切换策略。针对冷端系统,研究发现变负荷时存在最佳切泵点^[93],优化泵组切换时间点可使供电煤耗率降低0.50 g/(kWh)。针对脱硫系统,采用浆液循环泵自适应启停的定频运行优化控制策略后,瞬态过程脱硫系统能耗降低了23.05%^[94]。针对除尘系统,通过省煤器烟气旁路流量、低温省煤器冷却水流量与除尘电压的协同控制^[95],瞬态过程中电除尘系统能耗最大降低18.59%。上述研究表明,通过冷端、脱硫、除尘等辅机系统高效调控可实现燃煤发电机组的深度节能。

电力市场机制是指通过价格信号引导用户错峰用电,以竞争机制推动源网荷储协同优化,实现电力资源配置效率与能源利用效率的双重提升。其核心是基于边际成本或机会成本构建动态定价模型,将调频、调峰、备用等辅助服务的价值量化为可交易的经济信号^[96],驱动发电侧主动参与市场博弈,属于三次调频。在燃煤发电系统视角下,以利润最大化为目标,通过价格信号获得相同投资成本下调频能力提升的最优路径^[97]。随着电力现货市场与辅助服务市场深度融合,价格激励正从单一维度向多维竞争演进,在提升系统调峰调频能力的同时实现发电侧利润最大化,并有效支撑高比例可再生能源并网需求,实现电力系统安全经济运行。

4 总结与展望

燃煤发电作为保障我国能源电力安全的压舱石,技术演进始终聚焦能效提升、减排控制与成本效益优化。本文从热经济性定量分析方法、稳态工况节能方

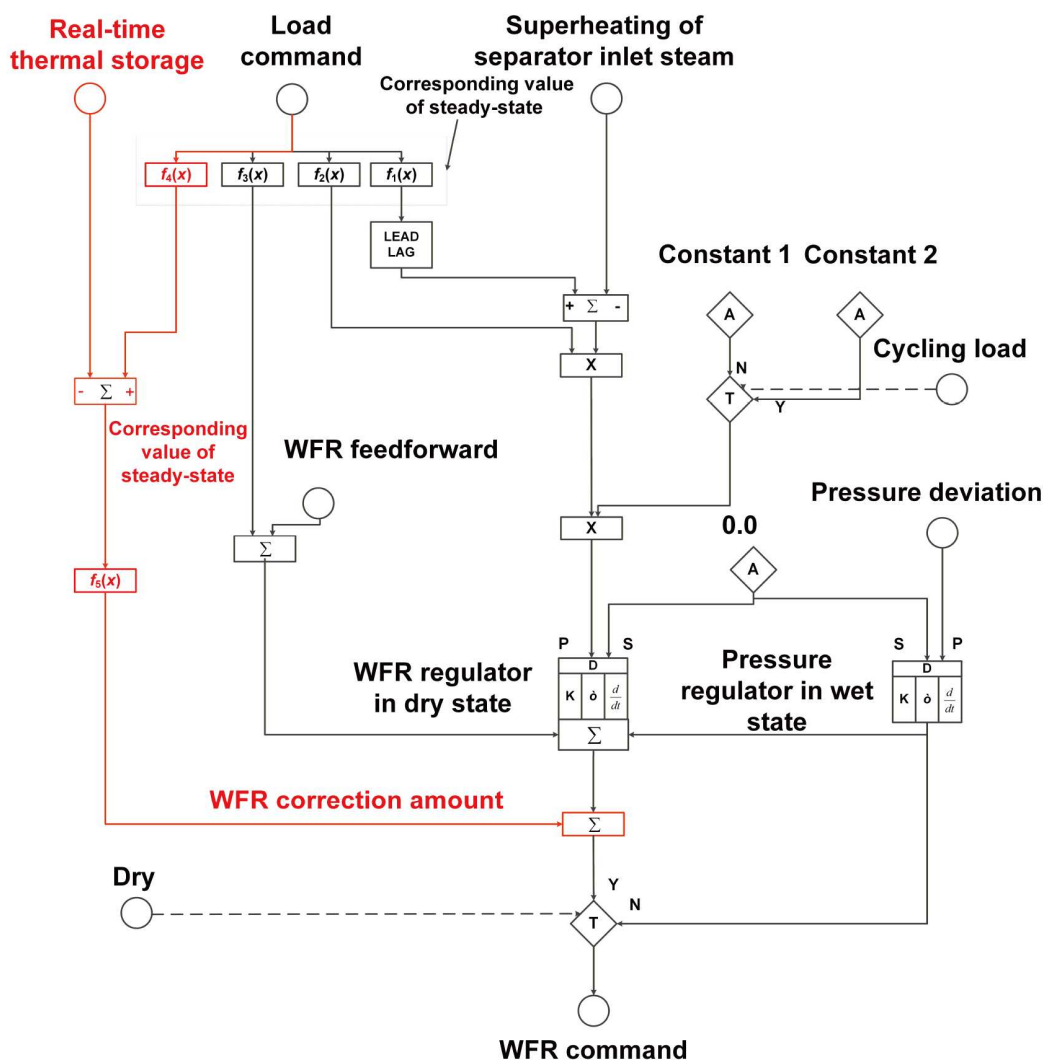


图 6 燃煤发电系统主动调控蓄热的风-煤-水控制策略^[86]

Figure 6 The wind-coal-water control strategy based on heat storage in a coal-fired power plant^[86]

法及变负荷瞬态过程节能方法三方面系统总结了燃煤发电系统节能的研究进展.

系统热经济性定量分析方法已从稳态工况拓展至瞬态过程, 并从机理分析逐步演进为机理-数据混合分析模式。稳态工况节能方法包括蒸汽初参数提升、排汽终参数优化、回热系统设计优化、再热参数选择及机炉耦合流程重构等, 深度调峰工况节能方法正在逐步完善。变负荷瞬态过程节能方法包括基于热力学分析主动调控蓄热的控制策略优化与大数据驱动的控制参数优化, 通过多变量动态优化降低瞬态过程能耗, 并在主机控制和辅机控制方面形成了完整的节能方法, 同时电力市场采用价格激励机制进一步完善辅助服务

市场交易机制.

“双碳”目标下,燃煤发电系统长时间处于调峰调频过程的新运行模式,未来亟需聚焦超低负荷下燃煤发电节能方法、突破更高参数等级的热力循环优化方法及构建燃煤发电智能化精准调控方法三方面研究。一是聚焦超低负荷下燃煤发电节能方法。随着新能源渗透率持续攀升,燃煤发电需具备超低负荷(<20%额定负荷)运行能力,未来需要聚焦超低负荷下锅炉稳燃、汽轮机通流部分安全、系统工质外排和辅机系统能耗增加等瓶颈难题,对采用耦合外部储能设备参与深度调峰的系统,亟需解决系统间能势精准匹配等问题。二是突破更高参数等级的热力循环优化方法。700℃等级

超超临界燃煤发电技术可将供电效率提升至50%以上,未来亟需解决700℃锅炉/汽轮机一体化匹配方法和超高参数热力循环构建与优化方法等。三是构建燃煤发电智能化精准调控方法。为了进一步提升燃煤发电系

统节能效果和运行安全性,智慧化是未来发展趋势,需要聚焦热力循环机理和大数据大模型深度融合的节能方法研究,实现智能控制、智能巡航、智能监盘“三位一体”的智慧运行。

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Summary for “面向新型电力系统的燃煤发电系统节能方法研究进展”

Research progress on energy-saving methods for coal-fired power systems in the new power system

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“Energy Conservation Priority” is a long-term strategy adhered to in China’s economic and social development. The coal-fired power system, as the anchor for ensuring China’s energy and electricity security, has consistently focused its technological evolution on enhancing energy efficiency, emission control, and cost-effectiveness optimization. Under the “dual carbon” goals, the coal-fired power system is transitioning from the primary power source to a regulating power source, with a dramatic increase in peak-shaving and frequency-modulation tasks. In this new context, achieving deep energy conservation in coal-fired power systems during peak-shaving and frequency-regulation processes has become a major national strategic need to support the construction of a new power system.

This manuscript systematically summarizes the research progress in energy conservation for coal-fired power systems from three aspects: quantitative analysis methods for thermal economy, energy-saving methods for steady-state operating conditions, and energy-saving methods for transient processes under variable loads.

The long-term focus of quantitative analysis methods for system thermal economy has been on design conditions, primarily including the conventional heat balance method, cycle function method, equivalent heat drop method, and specific consumption analysis method. Based on thermodynamic principles, these methods determine the impact mechanisms of parameter deviations on energy consumption and extend these methods to variable operating conditions and multiple-type power systems. In recent years, thermal economy quantitative analysis methods have expanded from steady-states to transient processes, adopting additional energy consumption evaluation and data-driven analysis to characterize time-varying characteristics and quantify energy-saving potential, evolving from mechanism analysis to a hybrid mechanism-data analysis model.

Energy-saving methods for steady-state operating conditions include steam initial parameter improvement, exhaust terminal parameter optimization, regenerative system design optimization, reheat parameter selection, and turbine-boiler coupling process reconfiguration. Under deep peak-shaving conditions, system energy consumption surges and equipment safety risks intensify. Methods such as refined combustion adjustment, flow path modification, and variable frequency speed control are employed to achieve synergistic improvement in equipment safety and energy efficiency, while energy-saving methods for deep peak-shaving conditions still require further refinement.

The transient process under variable loads involves different time-scale processes, including primary frequency regulation (seconds), secondary frequency regulation (minutes), and tertiary frequency regulation (hours). Key energy-saving methods include optimization of main unit control strategies based on thermodynamic analysis for active regulation of heat storage, big data-driven optimization of main unit control parameters, optimization of auxiliary equipment transient control strategies, and improvement of electricity market trading mechanisms based on price incentive mechanisms.

To establish a clean, low-carbon, secure, and efficient new power system, future research urgently needs to focus on three aspects: energy-saving methods for coal-fired power under ultra-low loads, breakthroughs in thermal cycle optimization methods for higher parameter levels, and the construction of intelligent precision control methods for coal-fired power generation.

new power system, coal-fired power system, energy-saving methods, steady-state conditions, transient processes

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