热力循环

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铁载氧体整体煤气化链式燃烧联合循环系统性能研究

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摘　要: 化学链式燃烧能在能量释放的同时有效分离 CO_2。运用 ASPEN PLUS 软件对 FeO/ Fe_3O_4/ Fe_2O_3 作载氧体的整体煤气化链式燃烧联合循环系统性能进行了模拟研究, 分析空气反应器温度、冷却空气率、透平进口前补燃温度对系统效率、氧耗量和 CO_2 排放量等参数的影响。模拟结果表明, 维持透平进口前补燃温度 1 350 ℃, 当空气反应器温度从 850 ℃提高到 1 100 ℃时, CO_2 排放量从 396 g/(kWh) 降低到 210 g/(kWh), 系统效率从 44.04% 降低到 43.19%; 提高冷却空气率, 系统效率降低; 提高透平进口前补燃温度将增加 CO_2 的排放量; 在一定的透平进口温度下, 存在最佳压缩比。

关　键　词: 联合循环; 化学链式燃烧; 煤气化; CO_2 分离; ASPEN PLUS

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引　言

二氧化碳是主要的温室气体, 燃烧过程中减排 CO_2 已经成为当今研究的热点。常规火电技术均以空气为氧化剂, 生成的烟气中二氧化碳虽只占 10% ~20%, CO_2 的后续分离成本高, 难以实施。化学链式燃烧 (CLC-Chemical-Looping Combustion) 的主要思想是将燃烧器分成两个独立的过程: 氧化反应和还原反应, 如图 1 所示。以合适的金属氧化物作载氧体, 在两个反应器间交替循环, 空气与燃料气体不直接接触, 在燃料"燃烧"的同时, 有效分离 CO_2, 很好地解决了燃烧后 CO_2 的分离问题。燃料燃烧产物主要是由 CO_2 和水蒸气组成, 只要将水蒸气冷凝成水, 便可分离得到较纯净的 CO_2。Paul Cho 等人研究了以铁、镍和铜为载氧体时 CLC 系统的性能[1]; Lyngfelt 等人以 CH_4 为燃料, Fe_2O_3 和 NiO 作载氧体, 对化学链式燃烧锅炉进行概念设计, 研究了该金属氧化物的反应特性[2~4]。Anheden 对以煤气化合成气为燃料化学链式燃烧进行初步研究[5]。Eva Johansson 等人搭建了功率为 100 W 的化学链式燃烧实验装置, 以便对化学链式燃烧系统进行更加全面的研究[6]。金红光教授等人研究了多种气体燃料的 CLC 燃烧机理, 分析研究了相关联合循环的热力性能[7~8]; 向文国等人也对 CLC 相关的燃烧性能进行了仿真计算[9]。

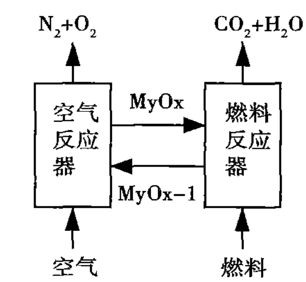

图 1　化学链置换燃烧原理

本文重点研究整体煤气化链式燃烧联合循环系统的性能和参数特性, 该系统在整体煤气化联合循环 (IGCC) 系统的基础上[10], 燃气轮机的燃烧室用 CLC 燃烧装置取代, 成为一个可以分离 CO_2 的系统, 同时加上 CO_2 压缩系统, 便于 CO_2 回收处理, 可实现燃煤发电近零排放。以 ASPEN PIUS 软件为工具, 对该系统进行模拟, 分析空气反应器温度、空气冷却率、透平进口前补燃温度、压气机压比等参数对系统性能的影响。

1　系统概述

铁载氧体整体煤气化链式燃烧联合循环系统, 主要由煤气化、CLC、燃气轮机、余热锅炉及汽水循环和二氧化碳压缩和分离等部分组成, 如图 2 所示。气化炉出口煤气经过净化, 作为燃料进入化学链式燃烧装置中的燃料反应器, 其出口烟气经过纯氧催化补燃后进入燃气透平 GT2 做功, 排气进入余热锅

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炉2,产生蒸汽供蒸汽轮机做功,最后排气进入二氧化碳压缩和分离系统得到液态的二氧化碳;空气经压气机压缩后进入空气反应器,其出口燃气(欠氧空气)进入补燃装置,经提高温度后进入燃气透平 GT1 做功,排气同样进入余热锅炉产生蒸汽做功,最后排入大气。

运用 ASPEN PLUS 软件模拟该系统的关键是确定系统的主要环节[11],并选择合理的单元操作模块,模拟各个主要环节。该系统的主要设备是气化炉、压气机、燃烧室、燃气透平、余热锅炉和蒸汽透平。其中压气机、燃气透平、蒸汽透平均用 Compr 模块代替。Compr 可以在给定一个出口压力规定时计算所需的功率,或者在给定功率时,计算出口压力。通过定义入口与出口的压力变化区分透平机与压气机,对压气机即为压比、透平则为膨胀比。余热锅炉用 MHeatX 模型代替。MHeatX 模型属于多物流换热器,这与用若干个 Heater(换热器)模型和热流来搭建余热锅炉的模型在原理上一样,但相对简单。气化炉、空气反应器、燃料反应器和燃烧器用 RGibbs 模型, RGibbs 使用均相的 Gibbs 自由能最小去计算平衡,不要求规定反应的化学计量系数。二氧化碳压缩、分离系统中的冷凝器用 Heater 模型模拟。

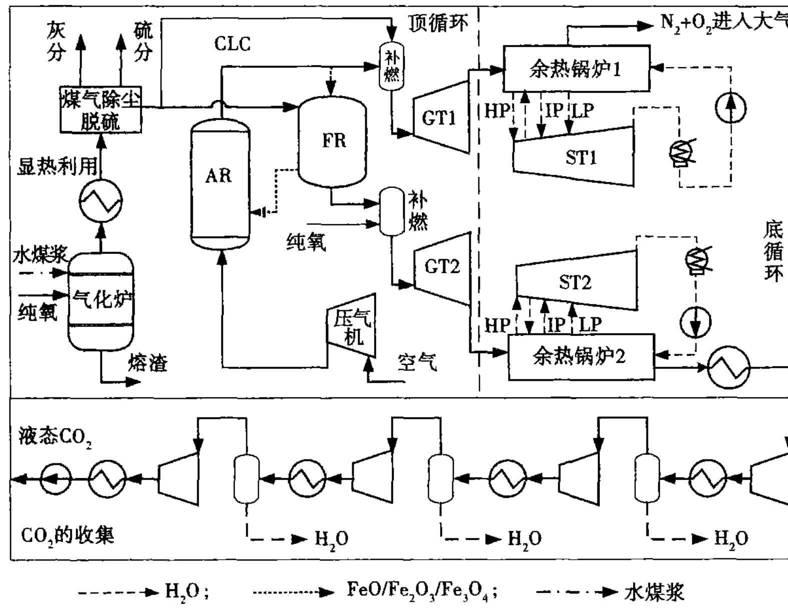

图 2 整体煤气化链式燃烧联合循环系统示意图

1.1 煤气化系统

系统选择德士古煤气化工艺,煤样选用国际研究中使用较多的伊里诺斯 6 号煤(Illinois 6 号),其成份如表 1 所示,高位热值为 26.14 MJ/kg,低位热值为 24.83 MJ/kg。

表1 伊里诺斯 6 号烟煤成份分析 (%)

C	H	O	N	S	水分	灰分	固定碳	挥发份
61.2	4.7	8.8	1.1	3.4	12.0	8.8	42.85	36.35

水煤浆和氧气进入气化炉,在气化炉内进行气化反应,主要生成 CO、H_2、CO_2、H_2O、CH_4、H_2S 和 N_2,以及少量的 NH_3、COS、HCN 和飞灰。经净化后,洁净煤气通入 CLC 燃烧系统。本文没有模拟空气分离系统,空分制氧功耗按经验数据 0.4 kWh/kg 折算[12],为系统耗功的一部分。

1.2 CLC 系统

选择 $FeO/Fe_2O_3/Fe_3O_4$ 为载氧体。在空气反应器中,载氧体发生氧化反应:

$$6FeO+O_2\rightarrow 2Fe_3O_4-620.55\ kJ/mol \quad (1)$$

$$4Fe_3O_4+O_2\rightarrow 6Fe_2O_3-464.64\ kJ/mol \quad (2)$$

$$4FeO+O_2\rightarrow 2Fe_2O_3-568.61\ kJ/mol \quad (3)$$

燃料反应器发生反应:

$$Fe_3O_4+CO\rightarrow 3FeO+CO_2+27.1\ kJ/mol \quad (4)$$

$$Fe_3O_4+H_2\rightarrow 3FeO+H_2O+68.28\ kJ/mol \quad (5)$$

$$Fe_2O_3+CO\rightarrow 2FeO+CO_2+1.1\ kJ/mol \quad (6)$$

$$3Fe_2O_3+H_2\rightarrow 2Fe_3O_4+H_2O-9.64\ kJ/mol \quad (7)$$

$$3Fe_2O_3+CO\rightarrow 2Fe_3O_4+CO_2-50.82\ kJ/mol \quad (8)$$

$$Fe_2O_3+H_2\rightarrow 2FeO+H_2O+42.29\ kJ/mol \quad (9)$$

煤气化反应参数确定后,满足链式反应平衡所需的最小载氧体质量 $m_{MO\text{-}min}$(kg/kg(Coal))和完全氧化所需的最小空气量 $m_{air\text{-}min}$(kg/kg(Coal))也随之确定[13]。

1.3 燃气轮机

燃气轮机是本系统主要的输出功设备。由于载氧体的特性,空气反应器出口烟气温度低于燃气轮机设计透平进口温度(TIT),为提高系统效率,在烟气进入透平前加以补燃。为衡量补燃的程度,定义补燃率:

$$补燃率=\frac{用于补燃的煤气量}{总的煤气量}\times 100\% \quad (10)$$

燃气轮机的效率和输出比功随 TIT 的升高而升高。TIT 温度越高,燃气透平需要从压气机抽取更

多的冷却空气。定义冷却空气率：

$$冷却空气率=\frac{用于冷却的压缩空气量}{压气机空气流量}\times 100\% \quad (11)$$

一般燃料反应器出口烟气中含有未反应的 H_2 和 CO 气体，既降低了系统效率，也会造成 CO_2 压缩耗功的增加。可通过纯氧催化燃烧，将 H_2 和 CO 转化为 H_2O 和 CO_2，提高了烟气温度，增加烟气做功能力。

1.4　余热锅炉及汽水循环系统

燃气透平进口温度选择在 1 350 ℃，其排气温度较高，选择三压再热余热锅炉，充分利用燃气余热。汽水系统流程如下：给水经泵升压进入低压省煤器，然后分成 3 股，一股进入低压蒸发器，一股经中压泵进入中压省煤器，一股经高压泵升压后，部分进入高压省煤器，部分先进入煤气冷却器后再进入高压过热器。

1.5　二氧化碳压缩、分离系统

对 CO_2 的压缩分 4 级进行，每一级都经过压缩、冷却、气液分离 3 个过程，直至 CO_2 变为液体，可由泵输送。定义 CO_2 回收率：

$$CO_2=\frac{经压缩分离得到的液态CO_2}{压缩得到的液态CO_2+余热锅炉1排气中CO_2} \quad (12)$$

2　结果与分析

模拟系统主要参数选择为：德士古气化炉气化温度定为 1 315 ℃，氧气纯度为 95%，压气机绝热效率为 88%，燃气透平绝热效率为 90%，三压再热型余热锅炉，高、中压蒸发器的节点温差为 15 ℃，低压蒸发器节点温差为 8 ℃。余热锅炉主蒸汽参数：12.5 MPa/566 ℃/2.62 MPa/566 ℃/0.72 MPa/232 ℃。二氧化碳压缩、冷却循环冷却入口水温 20 ℃，最大级压比为 3.5。

2.1　空气反应器温度对系统性能的影响

图 3～图 5 均为空气反应器温度对系统参数的影响。燃气透平进口温度 1 350 ℃，冷却空气率 8%。由图 3 可知空气反应器温度升高，由于空气反应器出口燃气量较燃料反应器出口烟气量大，用于补燃的燃料量减少，补燃率从 57.49% 降低到 29.99%。由图 4 可知，随着空气反应器温度的升高，补燃率降低，燃料反应器燃料量消耗增加，其出口烟气中未反应的 H_2 和 CO 气体增加，用于催化燃烧的纯氧量增加，系统氧耗量增加。由于空气分离制氧功耗增加，系统净效率下降，空气反应器温度从 850 ℃升高到 1 100 ℃，系统效率由 44.04% 降低到 43.19%。从图 5 看出，空气反应器温度对 CO_2 回收率和排放量的影响。补燃率减少，补燃后烟气中 CO_2 含量减少，余热锅炉 1 排向环境的 CO_2 减少，空气反应器温度从 850 ℃升高到 1 100 ℃，CO_2 排放量由 396 g/(kWh) 减少到 210 g/(kWh)，回收率由 42.32% 增加到 69.75%。可见，提高空气反应器温度对 CO_2 减排效果明显。

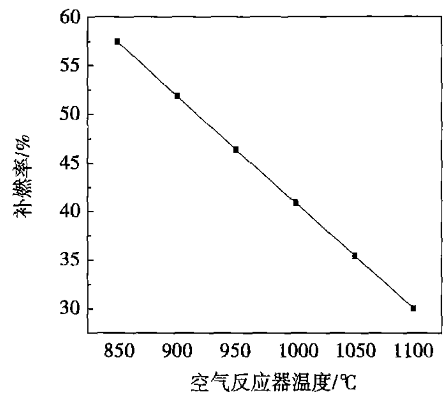

图 3　空气反应器温度对系统参数的影响

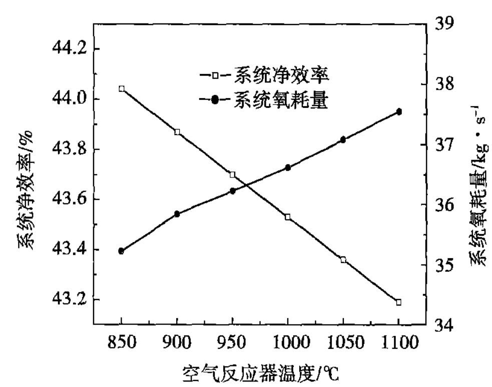

图 4　空气反应器温度对系统参数的影响

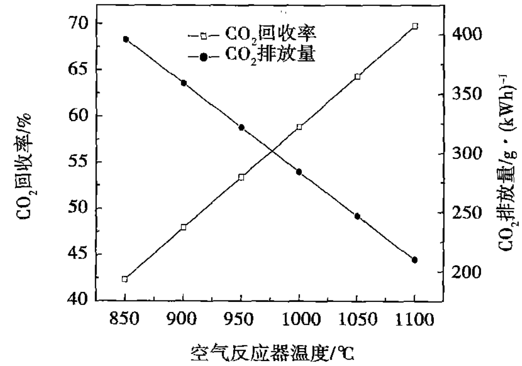

图 5　空气反应器温度对系统参数的影响

2.2　冷却空气率对系统性能的影响

图6是冷却空气率对系统参数的影响。选择空气反应器温度 1 050 ℃,透平进口前补燃温度 1 350 ℃,补燃率 35.4%。冷却空气率从 6%～16%变化时,转子进口平均温度降低,系统净效率降低。补燃率一定,排向环境的 CO_2 量不变,系统效率降低,单位质量燃料做功减少,单位输出功率 CO_2 排放量略有增加(增加约 5 g/(kWh))。不考虑 CO_2 压缩耗功,系统效率要比考虑压缩功后的净效率高约 2%。

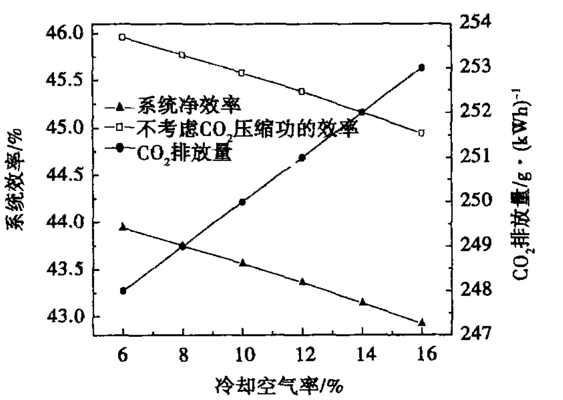

图 6　冷却空气率对系统参数的影响

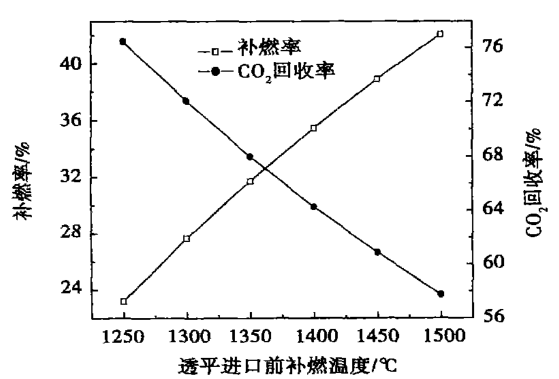

图 7　透平进口前补燃温度对系统参数的影响

2.3　透平进口前补燃温度对系统性能的影响

图7是透平进口前补燃温度与补燃率和 CO_2 回收率的关系。空气反应器温度为 1 050 ℃。由图可知,随着透平进口前补燃温度的提高,用于补燃的燃料量也迅速增加,补燃率不断升高,补燃后燃气中 CO_2 含量升高,回收率下降。当补燃温度由 1 250 ℃升高到 1 500 ℃时,CO_2 的回收率由 76.49%降低到 57.74%。但是,透平进口前补燃温度提高,燃气透平做功能力增加,系统效率得到提高。当补燃温度由 1 250 ℃升高到 1 500 ℃时,系统效率将从 41.7%升高到 44.45%。

2.4　压缩比对系统性能的影响

上述比较分析都是在相同压气机压比(压比17)条件下进行的,而压比是一个重要参数。设定透平进口前补燃温度分别为 1 400 ℃和 1 350 ℃,由图8可以看出,在一定的透平进口温度下,系统净效率都先增大后减小,存在一个最佳值。透平进口温度为 1 400 ℃和 1 350 ℃时,最佳压缩比分别为 19 和 17。随着透平进口温度的提高,最佳压比呈增大趋势。随着压比的升高,CO_2 排放量增加,原因是补燃率有所升高。

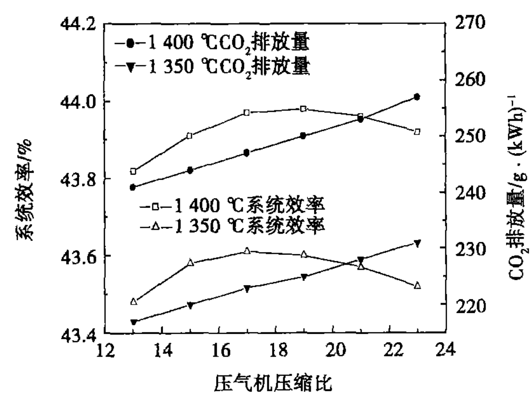

图 8　压缩比对系统参数的影响

3　结　论

化学链式燃烧能实现燃料"燃烧"的同时,有效分离 CO_2,将化学链式燃烧与整体煤气化联合循环技术结合,实现了燃煤高效发电的同时,很好地解决了 CO_2 的分离问题。本文通过对整体煤气化链式燃烧联合循环系统的研究,得到如下结论:

(1) 维持透平进口前补燃温度 1 350 ℃,当空气反应器温度从 850 ℃提高到 1 100 ℃时,CO_2 排放量从 396 g/(kWh)降低到 210 g/(kWh),其排放量远低于煤粉电厂(超超临界煤粉电厂的排放量为 733 g/(kWh)),但系统效率将从 44.04%降低到 43.19%。

(2) 维持透平进口前补燃温度 1 350 ℃,补燃率 35.4%,冷却空气率从 6%～16%变化时,转子进口平均温度降低,系统净效率降低约 1 个百分点。

(3) 当透平进口前补燃温度由 1 250 ℃升高到 1 500 ℃时,CO_2 的回收率由 76.49%降低到 57.74%。但是,透平进口前补燃温度提高,燃气透平做功能力增加,系统效率从 41.7%升高到 44.

45%。

(4) 透平进口温度为 1 350 ℃和 1 400 ℃时，最佳压缩比分别为 17 和 19。随着透平进口温度的提高，最佳压比呈增大趋势。

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（编辑　辉）

试验研究

涡轮轮盘榫槽的疲劳寿命试验

据《ASME Journal of Engineering for Gas Turbines and Power》2005 年 10 月号报道，为了研究某些涡轮轮盘榫槽的裂纹，建立了具有新的低循环和高循环不干涉加载型式的试验系统，以便研究涡轮盘纵树形榫槽在高温下的低循环和高循环联合的疲劳。

对于具有通过以相同的低周加载加上的等应力振幅分别为 50 Hz 和 100 Hz 的振动，完成了轻度的和严重腐蚀轮盘榫槽对比的低循环和高循环联合的疲劳寿命试验。通过第一个齿的实时裂纹探测，得到了纵树形榫槽裂纹扩展的规律—一种典型的多负荷通路结构。

最后，提出了一种新的双频率比方法，以便建立起试验的负荷和寿命与使用中相当的负荷和寿命之间相互的关系，使之有助于确定用于实践中严重腐蚀轮盘的破坏标准。

外推的结果表明，用于轻度腐蚀涡轮轮盘的寿命方针不能直接应用于严重腐蚀的轮盘，这是因为它的可靠寿命大大低于大修计划。因此，迫切需要考虑到严重腐蚀轮盘的使用情况建立新的标准，以便保证发动机结构的完整性。

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To raise initial parameters is an important measure for achieving energy savings and environmental protection, two national policies for coal-fired power plants. Under the condition of an enhanced initial steam temperature, the heat endurance properties of materials need to be upgraded simultaneously with the adoption of a steam cooling technology to lower the temperature and thermal stress of the turbine rotor, thereby guaranteeing the strength and service life of turbine parts and other components. In meeting the features of a quick and accurate calculation method required by engineering designs, a one-dimensional parameter calculation model was established for blade root cooling of rotors. The model can comprehensively accommodate all the influencing factors, including the jet-flow impact cooling of steam on the blade surface and heat conduction cooling by steam passing through the rotor root portion. The model has been used to calculate the temperature profile in the first stage of the medium pressure cylinder of a supercritical steam turbine unit. The comparison of the calculation results with three-dimensional ones indicates that the model can meet relevant engineering design requirements. **Key words**: supercritical steam turbine, rotor, steam cooling, cooling model

轴系特定结构扭转刚度及其对扭振特性的影响= **The Torsional Rigidity of a Shafting Specific Structure and its Effect on the Torsional Vibration Characteristics**[刊, 汉] /XIE Dan-mei, DONG Chuan (College of Power and Mechanical Engineering under Wuhan University, Wuhan, China, Post Code: 430072), LIU Zhan-hui (Henan Electric Power Test Academy, Zhengzhou, China, Post Code: 450052)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —146 ~148

With a domestically-made 660 MW supercritical steam turbine generator unit serving as an object of study, the torsion rigidity of shafting specific structures (such as stepped shaft, wholly-wrought wheel disks) and its effect on torsion vibration were calculated and discussed as a major focus. The formulae for calculating the material length λ in the stepped shaft not involved in the complete distortion was first derived with the λ value being determined in a range from 0 to $0.125\ d_1$。Then, a rigidity modeling method was presented for the material not involved in the complete distortion where there is an abrupt change in shaft diameter, unifying the treatment of the wholly-wrought rotor and stepped shaft. The calculation results of the shafting of a domestically-made 660 MW turbo-generator unit in a power plant indicate that the torsional vibration frequency obtained as a result of treating the shafting structure by using the derived formulae and modeling method under discussion is in good agreement with the result of empirical methods. The algorithm involved is characterized by its convenience for computer programming and assurance of a high calculation accuracy. **Key words**: turbo-generator unit, stepped shaft, wholly-wrought wheel disk, rigidity, torsional vibration

铁载氧体整体煤气化链式燃烧联合循环系统性能研究= **Performance Study of an Oxygen-bearing Iron Oxide-based Combined Cycle System Featuring Integrated Coal-gasification Chemical-looping Combustion**[刊, 汉] /MOU Jian-mao, XIANG Wen-guo (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology under the Southeast University, Nanjing, China, Post Code: 210096), DI Teng-teng (Sichuan Electric Power Vocational College, Chengdu, China, Post Code: 610072)// Journal of Engineering for Thermal Energy & Power. —2007, 22(2). —149 ~153

Chemical looping combustion can effectively separate out CO_2 with a simultaneous release of energy. A simulation study of the performance of a combined cycle system featuring integrated coal-gasification chemical-looping combustion with $FeO/Fe_3O_4/Fe_2O_3$ serving as an oxygen carrier has been conducted by using software ASPEN PLUS. In the meantime, the effect of air reactor temperature, cooling-air flow rate and supplementary firing temperature at the turbine inlet on such parameters as system efficiency, oxygen consumption rate and CO_2 emissions etc. was also studied. The simulation results indicate that when the supplementary firing temperature at the turbine inlet is kept at 1350 ℃ and the air reactor temperature increases from 850 ℃ to 1100 ℃, CO_2 emissions will drop from 396 g/(kWh) to 210 g/(kWh); the system efficiency will decrease from 44.04% to 43.19%. An increase in cooling-air flow rate will also reduce the system efficiency. When the supplementary firing temperature at the turbine inlet goes up, the CO_2 emissions will increase accordingly. There exists an optimum compression ratio at a given turbine inlet temperature. **Key words**: chemical-looping combustion, coal gasification, CO_2 separation, ASPEN PLUS

煤气化半焦增压流化床燃烧特性中试试验研究＝**An Experimental Study of the Combustion Characteristics of Coal Gasification Semi-coke in a Pilot-scale Pressurized Fluidized Bed**[刊，汉] /XIONG Yuan-quan, JIN Bao-sheng, XIAO Rui (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology, Thermal Energy Engineering Research Institute under the Southeast University, Nanjing, China, Post Code: 210096), ZHENG Shou-zhong (China State Water Conservancy and Hydropower Materials Co. Ltd., Beijing, China, Post Code: 100053)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —154～157

On the pilot-scale test run device of a pressurized fluidized bed with a thermal input of 1 MW, an experimental study of pressurized combustion has been conducted of the semi-coke obtained from the partial gasification of coal. The test results show that various sub-systems in the pilot-test run device for the coal gasification semi-coke are rational in design and the whole system can ensure a harmonious and reliable operation. Under the condition featuring a pressure of 0.5 MPa in the combustion chamber, a combustion temperature of 900 ℃, excess air ratio of 1.2 to 1.3 and fluidized speed of 1.1 to 1.2 m/s, the combustion efficiency of the semi-coke can exceed 99% with the carbon content of fly ash being below 2%. In addition, it has been also found that properly raising the bed temperature for semi-coke combustion and employing a suitable excess air ratio will contribute to a complete and steady combustion of the semi-coke while the circulation of the fly ash can be very beneficial to enhancing semi-coke combustion efficiency. **Key words**: semi-coke, combustion, pressurized fluidized bed, partial coal gasification, bed temperature

方形分离器结构优化试验研究＝**An Experimental Study of the Structural Optimization of Square Shaped Cyclone Separators**[刊，汉] /WANG Yu-zhao (Thermal Energy Engineering Department, Chengde Petroleum School, Chengde, China, Post Code: 067000), YANG Hai-rui, YUE Guang-xi (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —158～162

On a cold-state test rig, a structural optimization study has been conducted of a square shaped cyclone separator having an inlet of characteristic dimension $D=300$ mm with an acceleration section. The study results show that with an increase in core tube diameter (d) and core tube inserting depth (s), the separation efficiency tends to go up at the beginning followed by a decrease. The inlet height-width ratio (a/b) and straight section height (h) have an interactive impact on the separation efficiency. With an increase in inlet height-width ratio a/b, the separation efficiency goes up first and then decrease. When the inlet height-width ratio undergoes a change, the separation efficiency tends to change differently with a change in straight section height. When a/b is above 5.92, the separation efficiency will go down first with an increase in straight section height and then rise, attaining a minimum value at $h/D=2.3$. When a/b is below 5.92, the above efficiency will decrease with an increase in straight section height. The resistance of the cyclone separator will increase with an increase in the inlet height-width ratio and decrease with an increase in straight section height. The optimized values of the four parameters can be given as follows respectively: $d=0.4D$, $s=0.6D$, $a/b=8$ and $h=1.8D$. In such a case, the corresponding resistance of the cyclone separator will be 1.22 kPa. **Key words**: circulating fluidized bed boiler, square shaped cyclone separator, structural optimization, experimental study

锅炉"内爆"的动态模拟和预测＝**Dynamic Simulation and Forecast of "Boiler Implosion"**[刊，汉] /ZHAO Zhen-zhou, JIN Bao-sheng, XIONG Yuan-quan (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology, Thermal Energy Engineering Research Institute under the Southeast University, Nanjing, China, Post Code: 210096), SUN Ke-qin (Jiangsu Suyuan Environmental Protection Project Stock Co. Ltd., Nanjing, China, Post Code: 210024)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —163～167

The pressure fluctuations caused by a boiler implosion can affect the whole boiler flue gas and air system. Up to now, no relevant literature concerning three-dimensional numerical simulation of boiler flue gas and air systems has been found in China. To study the boiler implosion, a dynamic mathematical model has been established. Based on a CFD (computa-