氢能燃气轮机循环低温能有效利用及热力学分析

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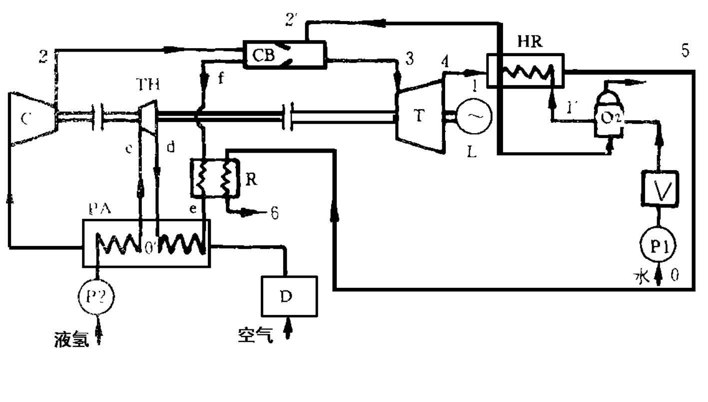
[摘要] 为了充分利用液氢的低温火用 ,在氢能燃气轮机循环中附加了一个空气预冷器和氢气透平。该循环的比功、热效率、火用效率均较简单循环燃气轮机有很大提高。本文对液氢 – 燃气动力循环进行了热力学分析 ,指出它的优越的动力性能。

关键词 氢能燃气轮机循环 低温火用 热效率 火用效率
中图分类法 TK479

1 循环工作过程

氢是代替常规燃料的理想的二次能源。它来源丰富 ,发热值高 ,燃烧无污染。液氢的热值是汽油的三倍 ,将它作为燃气轮机的替代燃料 ,可利用的不仅有它的化学火用 ,而且还有低温火用。本循环在简单燃气轮机循环的基础上 ,附加了空气预冷器、氢气透平和余热锅炉等装置。



PA – 空气预冷器 ; T – 燃气轮机 ; CB – 燃烧室 ; C – 压缩机 ; D – 干燥室 ; L – 负载 ; R – 回热器 ; P1, P2 – 泵 ; HR – 余热锅炉 ; M – 混合室 ; O2 – 除氧器 ; TH氢气透平 ; W – 水处理器。

图 1 循环示意图

氢能动力循环示意图如图 1所示。它包括氢系统、空气系统、燃气和水蒸气的双工质系统。

具有较低温度和一定压力的液氢首先进入空气预冷器 ,被环境状态的空气加热后 ,形成气态的氢。气态氢在氢气透平中膨胀做功后 ,重新返回空气预冷器 ,继续加热。再次加热的氢气经回热器进入燃烧室 ,在燃烧室内与来自压缩机的空气燃烧。燃烧产物在混合室中与余热锅炉中喷入的过热蒸汽相混合 ,共同完成定压吸热过程。达到一定高温的混合气进入透平膨胀做功。

环境状态的空气经过干燥室去湿 ,预冷器冷却 ,压缩机压缩 ,然后在燃烧室内与氢气反应 ,完成燃烧吸热过程。

水经泵、水处理、除氧器后 ,进入余热锅炉中 ,被透平排气加热 ,蒸发成为过热蒸汽。

余热锅炉中产生的过热蒸汽的一小部分进入除氧器作为它的热源。为充分利用余热 ,经余热锅炉流出的排气再进入回热器中预热从氢气透平做功后排出的氢气 ,然后排入大气。

2 工质系统

2. 1 氢系统

本动力循环中氢不仅是燃料 ,而且是工质。它在预冷器中冷却空气 ,且在氢气透平中膨胀做功。预冷器中左部相对于单位质量流量的空气的能量平衡方程为:

$$V[C_{pHb,h}(T_H - T_b) + Q_H + C_{pHh,e}(T_c - T_H)] = C_{pa0',1}(T_0' - T_1) \quad (1)$$

由换热器的温度效率定义 ,可求出预冷器左部氢气的出口温度为:

$$T_c = Z_R T_0' + T_b(1 - Z_R) \quad (2)$$

氢气在氢气透平出口的温度为:

$$T_d = T_c[1 - Z_H(1 - \Phi_H^{-R_H/C_{pHc,d}})] \quad (3)$$

式中氢气在氢透平中的膨胀比Φ_H要和空气在压缩机中的压比 c相匹配 ,确保 P_b和 P_2大致相等 ,以便在克服全面的阻力后 ,能进入燃烧室。

预冷器右部的能量平衡方程为:

$$VC_{pHd,e}(T_e - T_d) = C_{pa0,0'}(T_0 - T_0') \quad (4)$$

收稿日期 1997 – 03 – 06 收修改稿 1997 – 10 – 24
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设预冷器两侧的温度效率相等,则预冷器右侧出口的氢气温度为:

$$T_e = Z_R T_0 + T_d(1 - Z_R) \quad (5)$$

由以上五个方程和给定的 Z_R、Z_H、F_h、T_0值,可求出每阶段的温度及氢气透平的输出功率。

2.2　空气系统

空气经干燥室进入预冷器,在预冷器中分别被液氢和氢气冷却。空气温度由环境温度降到 T_1。由以上五个方程可求出 T_1 及预冷器中空气的温降比 θ。环境温度越高,与液氢的温差越大,预冷器中的传热越强烈,则空气的温降率越大。与相同环境状况的简单燃气轮机相比,循环的比功和效率都有较大提高。同时,由于压缩机入口空气的温度不会因环境温度的变化而有太大的波动,工况性能好,这也是利用液氢低温火用的一个重要优点。

由氢燃烧反应的化学平衡方程及燃烧的能量平衡方程,可以推导出氢燃料和空气的质量流量比为:

$$V = \frac{(1-a)C_{pg3'3}T_0\theta[f-1-(1/Z_c)(c^{R_a/C_{pa1,2}}-1)] + U C_{ps2'3}[Z_T(1-\Phi_T^{-R_g/C_{pg3,4}})-50]}{(C_{pg3'3}/C_{pg2'3})Z_B H_u - C_{pg3'3}T_0\theta[f-1-(1/Z_C)(c^{R_a/C_{pa1,2}}-1)]} \quad (6)$$

2.3　蒸汽和燃气双工系统

为充分利用透平的排气能量,透平后附设了余热锅炉,所产生的过热蒸汽回注入混合室,与高温燃气混合并使之降温后,进入透平膨胀做功,形成双工质循环。这既利用了透平排气能量,又减少了降温用空气量,同时使透平工质流量增加,一举三得,使机组效率和出力显著增加。

循环空气、氢气、燃气和过热蒸汽的热力过程曲线示于图2。图中0-1-2是空气的工作过程;2-3′是燃烧过程;3′-3和2′-3是燃气和蒸汽的混合过程;1′-2′是过热蒸汽的形成过程;3-4-5-6是混合气的工作过程;2′-2a是蒸汽的绝热节流过程;b-c-d-e-f是氢的工作过程。

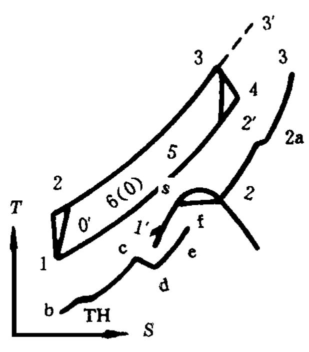

图 2　循环的 T-S 图

蒸汽参数必须与燃气参数相互匹配。余热锅炉蒸汽出口压力 $P_{2'}$ 应稍高于燃烧室的压力 P_2。本文取 $P_{2'} = 1.05P_2 = 1.05P_1 c$。

无补燃余热锅炉不同于一般燃烧锅炉,炉内温差较小。由于冷工质有相变,冷热工质的最小温差为节点温差 ΔT_s。根据文献[1]的推导原则,节点温差的计算式为:

$$\Delta T_s = T_5 - T_s + \frac{T_0\theta f[1-Z_T(1-H_T^{-R_g/C_{pg4,5}})] - T_5}{1 + \frac{r + C_{ps2's}\{T_0\theta f[1-Z_T(1-H_T^{-R_g/C_{pg4,5}})]-50-T_s\}}{C_{pL1',s}(T_s - T_1')}} \quad (7)$$

该温差必须大于零,否则余热锅炉将不能正常工作。因本文取 $T_4 - T_{2'} = 50℃$,因此 ΔT_s 不能大于50℃。ΔT_s的范围只能取 0℃ < ΔT_s < 50℃。同时,过热蒸汽的最大温度通常限定在 700℃,即 $T_{2'} < 700℃$。

图3是 ΔT_s随压比 c和升温比 f的变化曲线。图中可知,如果 $T_4 - T_{2'} = 50℃$,$T_{2'} = 600℃$,则 a-b-c线是 ΔT_s 的上界线。选择不同的 T_5时,图3中曲线的形式和循环工作范围将发生改变。

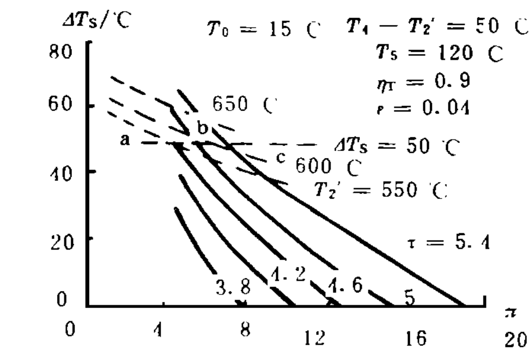

图 3　ΔT_s 随 c和 f的关系

由余热锅炉中的能量平衡方程可推出蒸汽和空气的质量流量比 U为:

$$U = \frac{(1-a+V)C_{pg4,5}\{T_0\theta f[1-Z_T(1-\varnothing_T^{-R_g/C_{pg3,4}})]-T_5\}}{T_0\theta f[1-Z_T(1-\varnothing_T^{-R_g/C_{pg}})](C_{ps}-C_{pg}) - C_{ps}(50+T_s) + C_{pg4,5}T_5 + QH + C_{PW}(T_s - T_1')} \quad (8)$$

3　分析及讨论

3.1　循环的比功输出和热效率

循环的比功和热效率由下两式给出:

$$W = VC_{pH_e,d}T_C Z_H(1-H_H^{-R_H/C_{pH_e,d}}) + (1+V+U-a)T_0\theta f C_{pg3,4s}Z_T(1-\varnothing_T^{-R_g/C_{pg3,4s}}) - (1/Z_C)T_0\theta C_{pa1,2}(c^{R_a/C_{pa1,2}}-1) \quad (9)$$

$$Z_{th} = W/[(1+V-a)C_{pa2,3}T_0\theta[f-1-(1/Z_C)(c^{R_a/C_{pa1,2}}-1)] + U(h_3 - h_{2'})] \quad (10)$$

按照这两个公式,绘成图4、5。图中可见,比功和热效率均较简单燃气轮机循环有较大提高。由图4可知,在节点温差 ΔT_s范围内,比功基本不随 c的变化而变化,曲线较平坦。以 f= 4.6为例,在工作范围内,比功较简单燃气轮机循环提高约 17.4%。

图5中的工作范围内,热效率与无预冷器的单一工质的简单燃气轮机相比有很大提高。以 f= 4.6, c= 10为例,热效率从 33% 增加到 40%,平均提高 7% 左右。

3.2　蒸汽空气流量比 U的影响

图 6给出了 Z_{th}、c、f、U、W 的关系曲线。图中可知，c一定时，随 U的增加，热效率和比功均增加，其中比功几乎是随 U的加大而直线上升。f一定时，U增加，比功的变化不大，热效率却急剧下降，蒸汽回注量增加，但因压比下降，引起膨胀比下降，它们对比功的影响相互抵消，因此比功变化不大。而 f不变时，U的增加是因膨胀比减少之故，此时比功减少燃料量却加大，所以循环效率显著下降。

U的大小取决于透平的排气能量，也即与循环的 c和 f有关。选择最佳工况时，必须考虑 U对其它参数的影响。按照本文给定的条件，U值取 0.15 - 0.175较好。

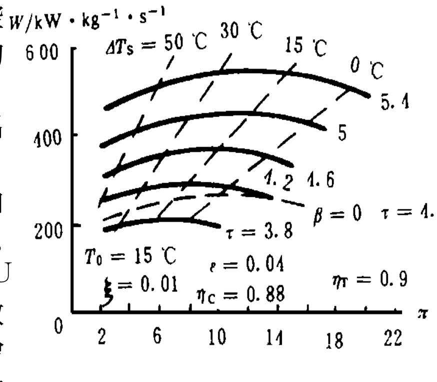

图 4　比功输出 W 和 c、f、ΔT_s 的关系

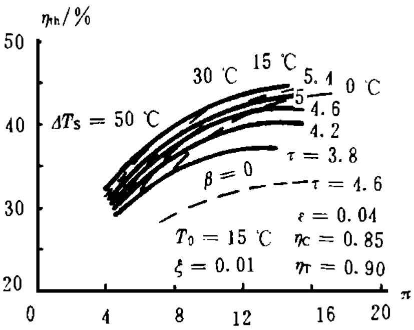

图 5　循环的 Z_{th} 和 c、f、ΔT_s 的关系

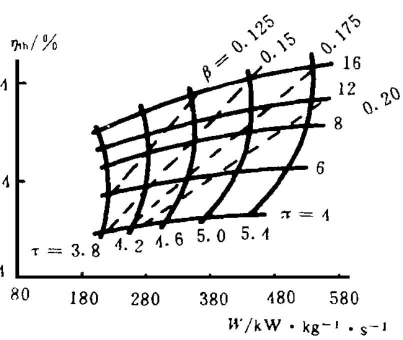

图 6　U对 Z_{th} 和 W 的影响

3.3　循环火用效率

液氢的火用包括燃料火用 e_0 和低温火用 e_L。通常取燃料火用 $e_0 = 0.95H_u$。低温的液氢是以降低空气温度以减少压缩机的输入，以及附加的氢气透平做功来将本身的低温火用转化成功的。低温火用的计算式为:

$$e_L = \int_{T_b}^{T_H}(1-T_0/T)C_{pLH}\mathrm{d}T + (1-T_0/T_H)Q_H + \int_{T_H}^{T_0}(1-T_0/T)C_{pSH}\mathrm{d}T \qquad (11)$$

液氢的总火用为:

$$e = e_0 + e_L = 0.95H_u + \int_{T_b}^{T_H}(1-T_0/T)C_{pLH}\mathrm{d}T + (1-T_0/T_H)Q_H + \int_{T_H}^{T_0}(1-T_0/T)C_{pSH}\mathrm{d}T \qquad (12)$$

通常，燃料火用随环境温度提高而下降，而低温火用随环境温度的升高而升高，这使总火用随环境温度升高而下降，循环的火用效率等于循环的总输出功与总火用之比，它可由公式(13)计算。

$$Z_{ex} = W/Ne_0 \qquad (13)$$

火用效率和 ç、f、ΔT_s 的关系示于图 7。与无预冷的情况相比，在 f相同时，火用效率较简单燃气轮机有很大提高。

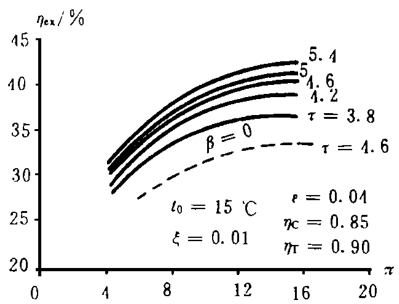

图 7　火用效率和 ç、f、ΔT_s 的关系 曲线

4　结论

(1) 该循环充分利用了液氢的低温火用和透平排气能量来提高循环热效率、火用效率和比功输出。

(2) 环境温度愈高，预冷效果越好，且该装置对工况变化有较强的适应性。

(3) 与普通燃气轮机具有同样功率输出的情况下，可以降低透平入口温度，提高机器寿命。

主要符号

$C_{pi,j}$ - 状态 i 和 j 间的平均定压比热 kJ/(kg.K); H_u - 氢的低温热值 kJ/kg; Q_H - 氢气的形成热 (kJ/kg; r - 蒸汽的形成热 kJ/kg; Z_c - 压缩机的绝热效率; s - 熵 kJ/(kg.K); Z_R - 预冷器的温度效率; Z_{th} - 热效率: T_s - 饱和温度 K; Z_T - 透平的绝热效率; c - 增压比; U - 蒸汽对空气的流量比; θ - 预冷器的温降比; V - 氢气对空气流量比; a - 泄漏系数; X - 压力损失系数; f - 循环的升温比 (T_3/T_0); Z_B - 燃烧效率; H - 膨胀比。

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(复　编)

压气机的湿压缩特性及计算模型初步研究= **A Preliminary Study of Compressor Wet Compression Characteristics and its Calculation Model**[刊,中]/Lin Feng, Wen Xueyou (Harbin No. 703 Research Institute)//Journal of Engineering for Thermal Energy & Power). -1998, 13(6). -402~405

After analyzing a huge amount of information and data published abroad concerning water spray into a compressor flow path and on the basis of the preliminary test results already obtained the authors sum up the main features of the compressor performance after a water spray and key factors which can exercise an influence on the compressor performance. A theoretical analysis and argumentation/justification of these features have been conducted. Finally, a calculation model is proposed based on the features of "wet compression". Key words: compressor, wet compression, model

锅炉过热器汇流集箱流动机理研究= **A Study of the Flow Mechanism in the Collector of a Boiler Superheater**[刊,中]/Wang Junye, Wu Guojiang, Wang Deping, et al (Shanghai Jiaotong University)//Journal of Engineering for Thermal Energy & Power). -1998, 13(6). -406~408

The uniform distribution of flow in a boiler header constitutes one of the key technological factors ensuring the safe design of boiler superheaters and reheaters. On the basis of momentum conservation this paper focuses on the study of flow mechanism of the header and its flow static pressure distribution. Furthermore, an analysis is also conducted of the basic governing rules and design parameters of the flow in the boiler header. Key words: boiler, header, superheater, branch flow, reheater

电站辅机可靠性考核验证方案= **A Reliability Verification Scheme for Power Station Auxiliaries**[刊,中]/Xu Hongquan, et al (China National Aviation Comprehensive Technology Research Institute)//Journal of Engineering for Thermal Energy & Power). -1998, 13(6). -409~411

MTBF(mean time between failure) and AF (availability factor) indexes are employed to verify the reliability of power station auxiliaries. Presented is a scheme for reliability index verification of power station auxiliaries by the use of power station on-site operation data along with some pertinent practical examples. This can serve as a guide for power station auxiliaries manufacturers and electric power operation departments in formulating reliability verification methods. Key words: power station auxiliaries, mean time between failure, availability factor, reliability verification test

自然循环锅炉启动过程中过热器超温机理的研究= **A Study of the Overheating Mechanism of Superheaters During Start-up of Natural Circulation Boilers** [刊,中]/Yan Weiping (North China University of Electric Power Engineering)// Journal of Engineering for Thermal Energy & Power). -1998, 13(6). -412~414

On the basis of a heat balance principle presented in this paper is a simple and intuitive analytical method of calculation for analysing and substantiating the underlying cause of superheater overheating during a boiler start-up. The results obtained agree well with those of actual measurements. The essence of superheater overheating during the boiler start-up is hereby clarified, which can have a certain reference value for the study of the superheater overheaitng mechanism and the determination of measures for solving the superheater overheating issues. Key words: boiler, boiler start-up, superheater overheating

氢能燃气轮机循环低温能有效利用及热力学分析= **The Effective Utilization of Hydrogen Energy-based Gas Turbine Cycle Low-temeprature Energy and Its Thermodynamic Analysis** [刊,中]/Cao Huiling, Yu

Yiqin // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 415～417

To fully utilize the low-temperature exergy of liquid hydrogen, installed additionally in a hydrogen energy-based gas turbine cycle is an air precooler and hydrogen turbine. Such a cycle enjoys a significant enhancement in specific power, thermal efficiency and exergy efficiency as compared with a simple cycle gas turbine. A thermodynamic analysis of the liquid hydrogen-gas power cycle is conducted and the latter's superior power performance predicted. Key words: hydrogen energy-based gas turbine cycle, low-temperature exergy, thermal efficiency, analysis

管内复合强化传热技术及机理分析= **In-tube Combination Intensified Heat Transfer Technology and An Analysis of its Mechanism** [刊,中]/Gao Xiaotao (Jiangsu Provincial Electric Power Test & Research Institute)// Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 418～420

With respet to in-tube intensified heat transfer and combination intensified heat transfer technology presented in this paper is an analysis of resistance and heat transfer characteristics under turbulent flow conditions. Experimental research results of several kinds of combination intensified heat transfer techniques are also given. It is pointed out that the insertion of a partial tube length twisted tape with a counter rotation in a spiral-corrugated tube can be regarded as a highly effective combination intensified heat transfer technique. Key words: intensified heat transfer, combination intensified heat transfer, spiral-corrugated tube, twisted tape

碳钢-水热虹吸管内部强化传热机理研究= **A Study of the Internal Intensified Heat transfer Mechanism of a Carbon Steel-Water Thermosyphon Pipe** [刊,中]/Sun Shimei (Jiling Chemical Engineering Institute) // Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 421～423

On the theoretical basis of a microlayer evaporation model an analysis is conducted of the intensified boiling heat transfer mechanism of thermosyphon pipe with an internally installed shunt tube structure. Set up is an internal boiling heat transfer model for a shunt tube intensified thermosyphon pipe. In addition, seven different kinds of perforated shunt tube structure have been selected for comparison with smooth tubes and for experimental study in order to seek an optimum shunt tube structure. A huge amount of experimental data is synthesized to establish a dimensionless number equation for intensified boiling heat transfer. Key words: shunt tube, intensified boiling heat transfer, heat transfer model

煤颗粒流化床脱挥发份的实验研究= **An Experimental Study of the Devolatilization of a Coal Particle Fluidized Bed** [刊,中]/Zheng Shouzhong, Zeng Dong, Cai Song (Southeastern University)// Journal of Engineering for Thermal Energy & Power). - 1998, 13(6). - 424～426

A devolatilization test of coal particles was conducted on a small-sized fluidized bed test rig. Studied is the effect of bed layer temperature, coal type, ambient atmosphere and other factors on the changing behavior of such elements as C, H and N in the coal in the course of devolatilization. Key words: coal fluidized bed, devolatilization

里克型脉动燃烧技术工程化应用实验研究= **Experimental Research of Rijke Type Pulsating Combustion Technology and Its Engineering Applications** [刊,中]/Zhong Yingjie, Chen Fulian, Shi Zhuling, et al (Zhe-