INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 5, Issue 6, 2014 pp.701-708
Journal homepage: www.IJEE.IEEFoundation.org

Thermodynamic analysis for a regenerative gas turbine cycle in coking process

Zelong Zhang[1, 2, 3], Lingen Chen[1, 2, 3,], Yanlin Ge[1, 2, 3], Fengrui Sun[1, 2, 3]

[1] Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, China.
[2] Military Key Laboratory for Naval Ship Power Engineering, Naval University of Engineering, Wuhan 430033, China.
[3] College of Power Engineering, Naval University of Engineering, Wuhan 430033, China.

Abstract
A regenerative gas turbine cycle driven by residual coke oven gas is proposed in this paper. The thermal efficiency and the work output (per ton of coke) of the system are analyzed based on thermodynamics and the theory of gas turbine cycle. The influences of the gas release rate, the residual gas rate and the effectiveness of regenerator on the performance of the cycle are analyzed by using numerical examples. It is found that the work output increases with the increase of the residual gas rate while decreases with the increase of the gas release rate. The cycle with regenerator can reach higher thermal efficiency and bigger work output, which means that the coke oven gas is used more effectively. Moreover, there exist two optimal pressure ratios of compressor which lead the maximum thermal efficiency and the maximum specific work, respectively.
Copyright © 2014 International Energy and Environment Foundation - All rights reserved.

Keywords: Coke oven gas; Regenerative Brayton cycle; Thermodynamic analysis; Thermal efficiency; Work output.

1. Introduction
Steel is a crucial material in human technological development, and is widely used in our lives. China's iron and steel industry is the basis of the national economy, and has made considerable progress in the past two decades [1]. With technological progress and proper redistribution, China's iron and steel industry has made tremendous achievements in energy conservation [2-11]. However, in comparison with developed countries, there is a big potential to save energy in China's iron and steel industry.
Coke is one of the most important materials consumed by the steelmaking process. It performs several functions in the blast furnace. In the coking process, bituminous coals are carbonized, and form coke, tar and COG (coke oven gas). After residual heat recovery and a series of cleaning treatments, COG consists mainly of H2 and CH4. COG is a prime fuel which has high heating value. It is an important fuel in steelmaking process. In the process of steelmaking, in order to maintain the mass flow rate in a constant, the energy input must be residual. As for gas system of an integrated iron and steel plant, the COG is always residual. Furthermore, with the progress in steelmaking process and metallurgy technology, the amount of residual COG will be more and more. Make good use of the residual COG can decrease the energy consumption in steelmaking process. Sun et al [12] designed a cogeneration system for producing

coke and generating electricity based on the principle of comprehensive and stepped utilization of energy. In the system, clean power generation with high efficiency is realized by decreasing the amount of air required for coking and supplying the combined cycle with enriched COG as much as possible. Hu et al [13] analyzed material flow, energy flow and sulfur flow of coking process in integrated iron and steel plants, and indicated that the utilization of COG should take into account various factors including the optimization of iron and steel manufacturing process and gas balance of plant, etc.. Villar et al [14] analyzed new waste-to-energy technologies in continuous industries in terms of conversion, energy saving, heat recovery, electricity generation, transportation fuel, storing energy and fuel, environmental emission, and recycling management. Mert et al [15] provided exergoeconomic analysis of an electricity and thermal energy cogeneration plant in an iron and steel factory.

Considering energy saving in steelmaking process, this paper proposes a regenerative gas turbine cycle by using residual COG as fuel. This system can reach higher thermal efficiency because the regeneration can recovery a part of waste heat in exhausted gas, and the work output of the system can be used for generating electricity and driving blowers, etc. Furthermore, the thermal efficiency and work output of the system are analyzed based on classical thermodynamics and the theory of gas turbine cycles [16-31]. According to the thermodynamic analysis, one can estimate the system's work output in different amount of residual COG. This paper can provide a basis for the optimization of residual COG utilization in further steps.

2. System description

In the coking process, a large amount of COG is produced as a by-product. After residual heat recovery and a series of cleaning treatments, COG can be used as good fuel which consists mainly of H_2 and CH_4. Part of COG is used in other process of ironmaking, and the residual coke oven gas is used as fuel in the regenerative gas turbine cycle proposed in this paper in order to save energy. COG is compressed in gas compressor, then is mixed with compressed air and burned in combustion chamber. The working fluid flows through the turbine and generates power, and the regenerator recovers waste heat in exhaust gas. The system layout of the regenerative gas turbine plant in coking process is shown in Figure 1. Figure 2 is the corresponding T-s diagram of the system.

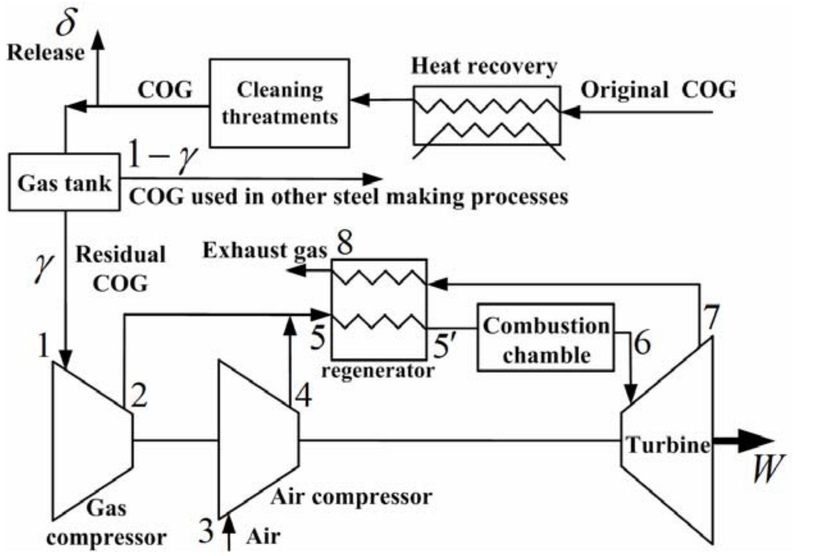


Figure 1. The system layout of a the regenerative gas turbine in coking process

3. Performance analyses

It is set that the COG's density is ρ_g=0.49 kg/m^3 and heating value is $H = 16.706\ \mathrm{MJ/m^3} = 34.0939\ \mathrm{MJ/kg}$. Producing one ton coke can generate COG of 430 m^3 or 210.7kg. The mass of residual COG is

$$m_g\ (\mathrm{kg}) = 210.7(1-\delta)\gamma \tag{1}$$

where δ is gas release rate, and γ is residual gas rate.

 ©2014 International Energy & Environment Foundation. All rights reserved.

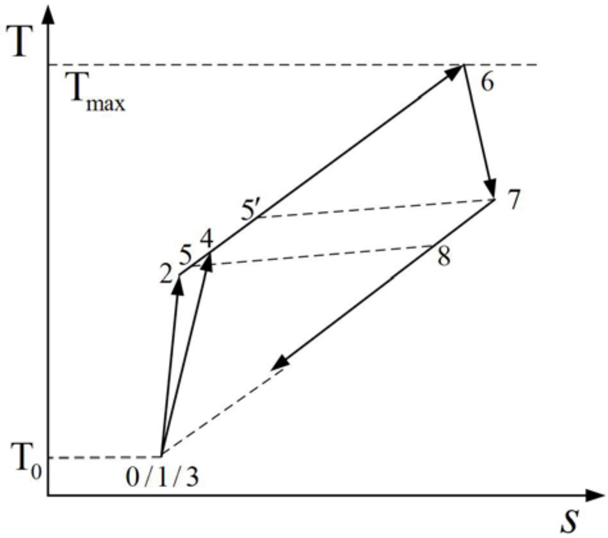


Figure 2. The T-s diagram of the system

Air consists 21% O_2 and 79% N_2 and its density is $\rho_a = 1.169\ \mathrm{kg/m^3}$. According to COG's components listed in Table 1 and air's components, one can obtain theoretical air quantity for complete combustion of $1\ \mathrm{m^3}$ COG:

$$L_0 = \frac{100}{21}\left[56.83\%/2 + 22.49\% \times 2 + 5.49\%/2 + 2.54 \times \left(\mathrm{n} + \mathrm{m}/2\right)\right] \approx 3.8638\ \mathrm{m^3} \tag{2}$$

Table 1. Proportions of COG's component $(T_0,\ p_0)$

Component	H_2	CH_4	CO	$N_2 + Ar$	CO_2	C_nH_m	Other components
Volume ratio	56.83%	22.49%	5.49%	10.26%	2.04%	2.54%	0.35%

The air-fuel ratio is

$$m_g / m_a = \frac{\rho_g}{\rho_a \lambda L_0} \tag{3}$$

where λ is excess air ratio, and m_a is mass of air.

The gas compression process is adiabatic and irreversible, the efficiency of gas compressor is defined as $\eta_{cg} = \left(T_{2s} - T_1\right)/\left(T_2 - T_1\right)$, the isentropic temperature ratio across the gas compressor is $T_{2s}/T_1 = \left(P_2/P_2\right)^{\frac{k_g - 1}{k_g}}$, and the temperature ratio of compression process is

$$\frac{T_2}{T_1} = \frac{T_2 - T_1}{T_{2s} - T_1}\left(\frac{T_{2s}}{T_1} - 1\right) + 1 = 1 + \left[\left(P_2/P_2\right)^{\frac{k_g - 1}{k_g}} - 1\right] \Big/ \eta_{cg} = 1 + \left({\varphi_{cg}}^{n_g} - 1\right) \Big/ \eta_{cg} \tag{4}$$

where T is temperature, P is pressure, k_g is specific heat ratio of COG, $n_g = \left(k_g - 1\right)/k_g$, and $\varphi_{cg} = P_2/P_1$ is pressure ratio of gas compressor.

The work required for gas compressor is

$$W_{cg} = m_g\left(h_2 - h_1\right) = m_g c_{pg} T_1 \left(T_2/T_1 - 1\right) = m_g\, c_{pg} T_1 \left({\varphi_{cg}}^{n_g} - 1\right) \Big/ \eta_{cg} \tag{5}$$

where c_{pg} is isobaric specific heat of COG and T_1 is ambient temperature.

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.

The air compression process is adiabatic and irreversible, the efficiency of air compressor is defined as $\eta_{ca} = (T_{4s} - T_3)/(T_4 - T_3)$, the isentropic temperature ratio across the air compressor is $T_{4s}/T_3 = (P_4/P_3)^{\frac{k_a-1}{k_a}}$, and the temperature ratio of compression process is

$$\frac{T_4}{T_3} = \frac{T_4 - T_3}{T_{4s} - T_3}\left(\frac{T_{4s}}{T_3} - 1\right) + 1 = 1 + \left[(P_4/P_3)^{\frac{k_a-1}{k_a}} - 1\right]\Big/\eta_{ca} = 1 + \left(\varphi_{ca}{}^{n_a} - 1\right)\Big/\eta_{ca} \tag{6}$$

where k_a is specific heat ratio of air, $n_a = (k_a - 1)/k_a$, and $\varphi_{ca} = P_4/P_3$ is pressure ratio of air compressor.
The work required for air compressor is

$$W_{ca} = m_a(h_4 - h_3) = m_g \frac{\rho_a \lambda L_0}{\rho_g} c_{pa} T_3 (T_4/T_3 - 1) = m_g \frac{\rho_a \lambda L_0}{\rho_g} c_{pa} T_3 \left(\varphi_{ca}{}^{n_a} - 1\right)\Big/\eta_{ca} \tag{7}$$

The inlet temperature of regenerator depends on the temperature of compressed gas and compressed air. The mixing process of gas and air is defined as ideal gas mixing process. According to the temperature and quality of compressed gas and compressed air, one can derive the inlet temperature of regenerator:

$$\begin{aligned} T_5 &= \frac{m_g T_2 + m_a T_4}{m_g + m_a} = T_2\left(\frac{1}{1 + \rho_a \lambda L_0/\rho_g}\right) + T_4\left(\frac{1}{1 + \rho_g/(\rho_a \lambda L_0)}\right) \\ &= T_1\left\{\left[1 + \frac{\left(\varphi_{cg}{}^{n_g} - 1\right)}{\eta_{cg}}\right]\left(\frac{1}{1 + \rho_a \lambda L_0/\rho_g}\right) + \left[1 + \frac{\left(\varphi_{ca}{}^{n_a} - 1\right)}{\eta_{ca}}\right]\left(\frac{1}{1 + \rho_g/(\rho_a \lambda L_0)}\right)\right\} \end{aligned} \tag{8}$$

The turbine expansion process is adiabatic and irreversible, the efficiency of turbine is defined as $\eta_t = (T_6 - T_7)/(T_6 - T_{7s})$, the isentropic temperature ratio across the turbine is $T_{7s}/T_6 = (P_7/P_6)^{\frac{k_w-1}{k_w}}$, and the temperature ratio of expansion process is

$$\frac{T_7}{T_6} = 1 - \frac{T_6 - T_7}{T_6 - T_{7s}}\left(1 - \frac{T_{7s}}{T_6}\right) = 1 - \eta_t\left[1 - (P_7/P_6)^{\frac{k_w-1}{k_w}}\right] = 1 - \eta_t\left[1 - \left(1 - 1/\varphi_t^{n_w}\right)\eta_t\right] \tag{9}$$

where $n_w = (k_w - 1)/k_w$ is specific heat ratio of working fluid (after air and gas being mixed and burned), and $\varphi_t = P_6/P_7$ is pressure ratio of turbine.
The work output of turbine is

$$\begin{aligned} W_t &= m_w(h_6 - h_7) = m_g\left(1 + \rho_a \lambda L_0/\rho_g\right) c_{pw} T_6 (1 - T_7/T_6)\eta_t \\ &= c_{pw} T_1 \tau m_g \left(1 + \rho_a \lambda L_0/\rho_g\right)\left(1 - 1/\varphi_t^{n_w}\right)\eta_t \end{aligned} \tag{10}$$

where c_{pw} is isobaric specific heat of working fluid, and $\tau = T_6 / T_1$ is temperature ratio of the system.
According to the balance of heat, $c_{pw}(T_7 - T_8) = c_{px}(T_{5'} - T_5)$, and the effectiveness of regenerator, $E_R = (T_7 - T_8)/(T_7 - T_5)$, the outlet temperature of regenerator is

$$T_{5'} = \frac{E_R \tau T_1\left[1 - \left(1 - 1/\varphi_t^{n_w}\right)\eta_t\right] + \left(c_{px}/c_{pw} - E_R\right)T_5}{c_{px}/c_{pw}} \tag{11}$$

where c_{px} is isobaric specific heat of mixed gas (air and gas are mixed before combustion).
According to the balance of heat in combustion chamber, the amount of heat added to the system is

 ©2014 International Energy & Environment Foundation. All rights reserved.

$$Q_{in} = c_{px}\left(m_a + m_g\right)\left(T_6 - T_{5'}\right) = c_{px} m_g \left(1 + \rho_a \lambda L_0 / \rho_g\right)\left(T_6 - T_{5'}\right) = m_g \eta_B H \tag{12}$$

Combing Eq. (2) with Eq. (11), the excess air ratio can be obtained

$$\lambda = \frac{\eta_B \rho_g H / \left[c_{px}\left(T_6 - T_{5'}\right)\right] - \rho_g}{\rho_a L_0} \tag{13}$$

The work output of the system is

$$\begin{aligned} W &= W_t - W_{cg} - W_{ca} \\ &= m_g T_1 \left[c_{pw}\tau\left(1 + \frac{\rho_a \lambda L_0}{\rho_g}\right)\left(1 - \frac{1}{\varphi_t^{n_w}}\right)\eta_t - \frac{c_{pg}\left(\varphi_{cg}{}^{n_g} - 1\right)}{\eta_{cg}} - \frac{\rho_a \lambda L_0}{\rho_g \eta_{ca}} c_{pa}\left(\varphi_{ca}{}^{n_a} - 1\right) \right] \end{aligned} \tag{14}$$

The thermal efficiency of the system is

$$\eta = W/Q_{in} = \frac{\begin{array}{l} c_{pw}\tau\eta_t(1+\rho_a\lambda L_0/\rho_g)(1-1/\varphi_t^{n_w}) - c_{pg}(\varphi_{cg}{}^{n_g}-1)/\eta_{cg} - \\ \rho_a\lambda L_0 c_{pa}(\varphi_{ca}{}^{n_a}-1)/(\rho_g\eta_{ca}) \end{array}}{\begin{array}{l} c_{pw}(1+\rho_a\lambda L_0/\rho_g)\{\tau - \{E_R\tau[1-\eta_t(1-1/\varphi_t^{n_w})] + \\ (c_{px}/c_{pw} - E_R)\{[1+(\varphi_{cg}{}^{n_g}-1)/\eta_{cg}][1/(1+\rho_a\lambda L_0/\rho_g)] + \\ [1+(\varphi_{ca}{}^{n_a}-1)/\eta_{ca}][1/(1+\rho_g/\rho_a\lambda L_0)]\}\}c_{pw}/c_{px}\} \end{array}} \tag{15}$$

From Eq. (15), one can see that the residual gas rate and the gas release rate have no influence on the thermal efficiency of the system.

4. Numerical examples

To see how the various parameters influence thermal efficiency and work output of the system, numerical examples are provided. In the calculations, it is set that the isobaric specific heat of air is $c_{pa} = 1.004\ \mathrm{kJ/(kg \cdot K)}$, isobaric specific heat of COG is $c_{pg} = 2.69\ \mathrm{kJ/(kg \cdot K)}$, the isobaric specific heat of mixed gas is $c_{px} = 1.006\ \mathrm{kJ/(kg \cdot K)}$, the isobaric specific heat of working fluid is $c_{pw} = 1.013\ \mathrm{kJ/(kg \cdot K)}$, the specific heat ratio of air is $k_a = 1.400$, the specific heat ratio of COG is $k_g = 1.351$, the specific heat ratio of working fluid is $k_w = 1.392$, the efficiencies of gas compressor and air compressor are $\eta_{ca} = \eta_{cg} = 0.9$, the efficiency of turbine is $\eta_t = 0.85$, the pressure ratios of gas compressor, air compressor and turbine are the same ($\varphi_{cg} = \varphi_{ca} = \varphi_t = \varphi_c$), the efficiency of combustion chamber is $\eta_B = 0.95$, the ambient temperature is $T_1 = T_3 = 300\mathrm{K}$, the ambient pressure is $P_1 = P_3 = 0.1013\mathrm{MPa}$, the temperature ratio of the cycle is $\tau = 5$, the effectiveness of regenerator is $E_R = 0.9$, the gas release rate is $\delta = 15\%$, and the residual gas rate is $\gamma = 20\%$.

Figures 3 and 4 show the influences of the gas release rate δ and the residual gas rate γ on the work output versus pressure ratio ($W - \varphi_c$) characteristic, respectively. One can see that the work output (per ton of coke) increases with increase in the gas release rate δ and decreases with the increase in the residual gas rate γ. In the practical steelmaking process, because of the heating value of coke oven gas is large, the residual coke oven gas should be used in generating electricity as much as possible. The amount of heat demanded in other procedures of steelmaking process can use blast furnace gas and basic oxygen furnace gas instead of coke oven gas. In this way, the amount of residual coke oven gas can be increased. Furthermore, the proper redistribution of the gas buffers such as gas tank and gas-fired boiler can decrease the gas release rate and make coke oven gas use effectively.

Figures 5 and 6 show the influences of the effectiveness of regenerator on the thermal efficiency versus pressure ratio (η - φ_c) and W - φ_c characteristics. When $E_R = 1$, both thermal efficiency η and work output W decrease with the increase in pressure ratio of compressor φ_c. When $E_R < 1$, there exist two

 ©2014 International Energy & Environment Foundation. All rights reserved.

optimal pressure ratios of compressor which lead to maximum thermal efficiency and work output, respectively. Furthermore, there is a critical pressure ratio of compressor, when φ_c is smaller than it, both thermal efficiency η and work output W increase with the increase in E_R; when φ_c is larger than it, both thermal efficiency η and work output W decrease with the increase in E_R.

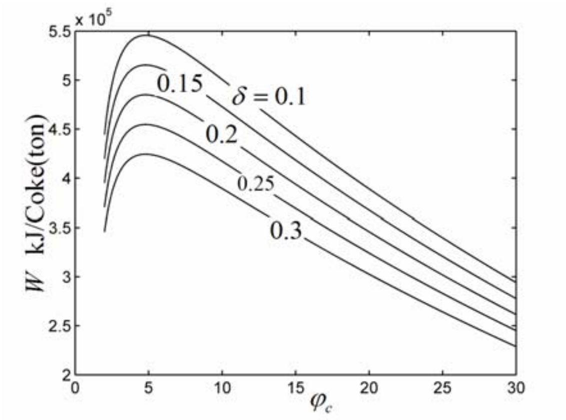


Figure 3. The influence of δ on the $W-\varphi_c$ characteristic

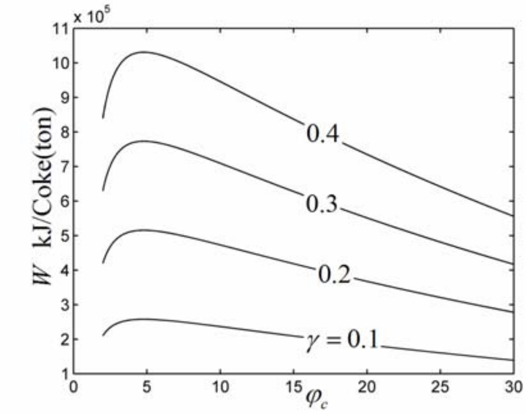


Figure 4. The influence of γ on the $W-\varphi_c$ characteristic

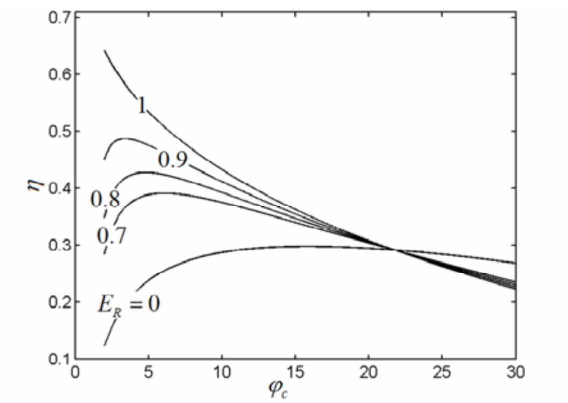


Figure 5. The influence of E_R on the $\eta-\varphi_c$ characteristic

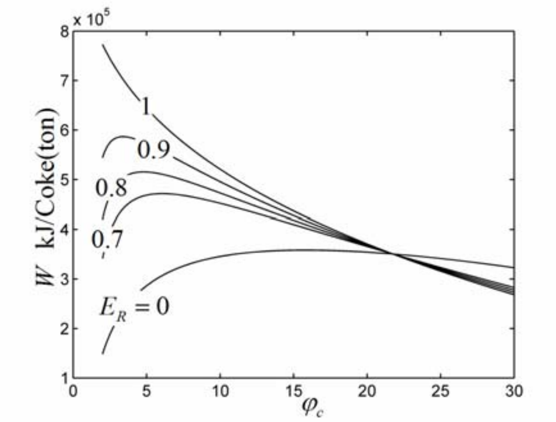


Figure 6. The influence of E_R on the $W-\varphi_c$ characteristic

5. Conclusion

In order to meet the needs in energy conservation of steelmaking industry, a regenerative gas turbine cycle by using residual COG as fuel is proposed in this paper. Work output of the system (the regenerative gas turbine cycle) can be used for generating electricity and driving blowers, etc. Furthermore, the thermal efficiency and work output of the system are analyzed based on classical thermodynamics and the theory of gas turbine cycle. Using numerical calculations, the effects of the gas release rate, the residual gas rate and the effectiveness of regenerator on the performance of the system are analyzed. One can see that the work output (per ton of coke) increases with increase in the gas release rate and decreases with the increase in the residual gas rate. In the practical steelmaking process, the proper redistribution of the gas buffers such as gas tank or gas-fired boiler can decrease the gas release rate and make COG be used effectively. In the system, when the pressure ratio is smaller than the critical one, both thermal efficiency and work output increase with the increase in effectiveness of regenerator, so the system with regenerator uses COG effectively. This paper analyzes the thermodynamic processes of the system, estimates the system's work output in different amount of residual COG and can provides a basis for the optimization of residual COG utilization in further steps.

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online) ©2014 International Energy & Environment Foundation. All rights reserved.

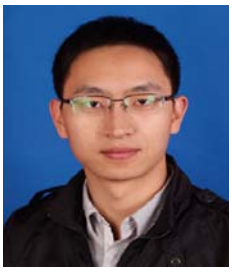
Acknowledgments
This paper is supported by the National Key Basic Research and Development Program of China ('973' Program) (Grant No. 2012CB720405) and the National Natural Science Foundation of P. R. China (Project No. 10905093).

References

[1] Y. Wei, H. Liao, Y. Fan, An empirical analysis of energy efficiency in China's iron and steel sector, Energy 32(2007) 2262-2270.
[2] National Bureau of Statistics of China, China Statistical Yearbook 2006, China Statistics Press, Beijing, 2006.
[3] OECD/ International Energy Agency, World Energy Outlook 2006, Paris, 2006.
[4] Z. C. Guo, Z. X. Fu, Current situation of energy consumption and measures taken for energy saving in the iron and steel industry in China, Energy 35(2010) 4356-4360.
[5] G. Ma, J. Cai, W. Zeng, H. Dong, Analytical research on waste heat recovery and utilization of China's iron & steel industry, Energy Proce. 14(2012) 1022-1028.
[6] W. Sun, J. Cai, Z. Ye, Advances in energy conservation of China steel industry, Sci. Word J (2013) Article ID 247035.
[7] H. Zhang, L. Dong, H. Q. Li, B. Chen, Q. Tang, T. Fujita, Investigation of the residual heat recovery and carbon emission mitigation potential in Chinese steelmaking plant: A hybrid material/energy flow analysis case study, Sust. Energy Tech. Assess. 2(2013) 67-80.
[8] M. Z. Stijepovic, P. Linke, Optimal waste heat recovery and reuse in industrial zones, Energy, 36(2011) 4019-4031.
[9] Y. Ammar, S. Joyce, R. Norman, Y. Wang, A. P. Roskilly, Low grade thermal energy sources and uses from the process industry in the UK, Appl. Energy 89(2012) 3-20.
[10] C. Gao, D. Wang, H. Dong, J. Cai, W. Zhu, T. Du, Optimization and evaluation of steel industry's water-use system, J. Cleaner Produ. 19(2011) 64-69.
[11] J. Gao, S. Li, Y. Zhang, P. Chen, P. Shen, Process of re-resourcing of converter slag, J. Iron & Steel Res., Inter. 18(2011) 32-39.
[12] S. Sun, H. Jin, L. Gao, W. Han, Study on a multifunctional energy system producing coking heat, methanol and electricity, Fuel 89(2010) 1353-1360.
[13] C. Hu, C. Zhang, X. Zhang, Y. Qi, R. Yin, Material and energy flow analysis of coking process in integrated steel plants, J. Iron Steel Res. 19(2007) 16-20 (in Chinese) .
[14] A. Villar, J. J. Arribas, J. Parrondo, Waste-to-energy technologies in continous process industries, Clean Tech. Environ. Policy 14(2012) 29-39.
[15] M. S. Mert, O. F. Dilmac, S. Ozkan, F. Karaca, E. Bolat, Exergoeconomic analysis of a cogeneration plant in an iron and steel factory, Energy 46(2012) 78-84.
[16] H. Sato, Cycle Theory of Gas Turbine, Sankaido, Tokyo, 1972.
[17] W. A. Woods, P. J. Bevan, D. I. Bevan, Output and efficiency of the closed-cycle gas turbine, Proc. IMechE, Part A: J. Power Energy 205(1991) 59-66.
[18] W. A. Woods, On the role of the harmonic mean isentropic exponent in the analysis of the closed-cycle gas turbine, Proc. IMechE, Part A: J. Power Energy 205(1991) 287-291.
[19] T. H. Frost, B. Agnew, A. Anderson, Optimization for Brayton-Joule gas turbine cycles, Proc. IMechE, Part A: J. Power Energy 206(1992) 283-288.
[20] P. Vadasz, D. Weiner, The optimal intercooling of compressor by a finite number of intercoolers, Trans. ASME, J. Energy Res. Tech. 114(1992) 255-260.
[21] C. A. Frangopoulos, G. G. Dimopoulos, Effects of gas-properties evaluation method on the optimal point of gas turbine cycles, Int. J. Thermodyn. 8(2005) 95-102.
[22] A. Calvo Hernandez, A. Medina, J. M. M. Roco Power and efficiency in regenerative gas turbine, J. Phys. D: Appl. Phys. 28(1995) 2020-2023.
[23] A. Calvo Hernandez, J. M. M. Roco, A. Medina, Power and efficiency in a regenerative gas-turbine cycle with multiple reheating and intercooling stages, J. Phys. D: Appl. Phys. 29(1996) 1462-1468.
[24] M. J. Naser, Exergy analysis and second law efficiency of a regenerative Brayton cycle with isothermal heat addition, Entropy 7(2005) 172-187.
[25] H. Zhao, P. F. Peterson, Multiple reheat helium Brayton cycles for sodium cooled fast reactors, Nucl. Eng. Des. 238(2008) 1535-1546.

 ©2014 International Energy & Environment Foundation. All rights reserved.

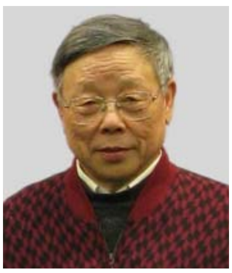
[26] R. Lugo, J. M. Zamora, M. Salazar, Optimum pressure ratio for complex gas turbine cycles, Inform. Tecn. 20(2009) 137-151.
[27] H. Chandra, A. Arora, S. C. Kaushik, Thermodynamic analysis and parametric study of a closed cycle gas turbine with intercooler and reheater on the basis of a new isentropic exponent, Int. J. Sust. Energy 30(2011) 82-97.
[28] J. H. Horlock, Advance Gas Turbine Cycles, 1st edition, Elsevier Science Publishers, London, 2003.
[29] H. Canière, A. Willockx, E. Dick, Raising cycle efficiency by intercooling in air-cooled gas turbines, Appl. Thermal Eng. 26(2006) 1780-1787.
[30] O. S. Sanjay, B. N. Prasad, Comparative evaluation of gas turbine power plant performance for different blade cooling means, Proc. IMechE, Part A: J. Power Energy 223(2009) 71-82.
[31] O. S. Sanjay, B. N. Prasad, Comparative performance analysis of cogeneration gas turbine cycle for different blade cooling means, Int. J. Thermal Sci. 48(2009) 1432-1440.



Zelong Zhang received his BS Degree in 2009 from the Huazhong University of Science and Technology and his MS Degree in 2011 from the Naval University of Engineering, P R China. He is pursuing for his PhD Degree in power engineering and engineering thermophysics from Naval University of Engineering, P R China. His work covers topics in finite time thermodynamics and technology support for propulsion plants. Dr Zhang is the author or coauthor of 10 peer-refereed articles (4 in English journals).

Lingen Chen received all his degrees (BS, 1983; MS, 1986, PhD, 1998) in power engineering engineering thermophysics from the Naval University of Engineering, P R China. His work cove diversity of topics in engineering thermodynamics, constructal theory, turbomachinery, reliat engineering, and technology support for propulsion plants. He had been the Director of the Departme Nuclear Energy Science and Engineering, the Superintendent of the Postgraduate School, and the Presi of the College of Naval Architecture and Power. Now, he is the Direct, Institute of Thermal Science Power Engineering, the Director, Military Key Laboratory for Naval Ship Power Engineering, anc President of the College of Power Engineering, Naval University of Engineering, P R China. Professor C is the author or co-author of over 1400 peer-refereed articles (over 620 in English journals) and nine b (two in English).
E-mail address: lgchenna@yahoo.com; lingenchen@hotmail.com, Fax: 0086-27-83638709 Tel: 0086-27-83615046

Yanlin Ge received all his degrees (BS, 2002; MS, 2005, PhD, 2011) in power engineering and enginee thermophysics from the Naval University of Engineering, P R China. His work covers topics in finite thermodynamics and technology support for propulsion plants. Dr Ge is the author or coauthor of ove peer-refereed articles (over 40 in English journals).



Fengrui Sun received his BS Degrees in 1958 in Power Engineering from the Harbing Universit Technology, P R China. His work covers a diversity of topics in engineering thermodynamics, constr theory, reliability engineering, and marine nuclear reactor engineering. He is a Professor in the Colleg Power Engineering, Naval University of Engineering, P R China. Professor Sun is the author or co-auth over 850 peer-refereed papers (over 440 in English) and two books (one in English)

 ©2014 International Energy & Environment Foundation. All rights reserved.