Thermodynamic Optimization of an Air bottoming Cycle for Waste Heat Recovery from Preheater Tower in a Cement Industry

Youcef Redjeb*, Khatima Kaabeche-Djerafi

LGPDDPS Laboratory, Department of Process Engineering, National Polytechnic School of Constantine, Constantine, Algeria

*Corresponding author: redjeb.youcef@gmail.com

Article Info

Article history:

Received 20 April, 2021
Revised 28 May, 2021
Accepted 07 June, 2021

Keywords:

ABC;
Waste heat;
Optimization;
Cement;
Exhaust gas;
Preheater;

ABSTRACT

This work evaluated the air bottoming cycles(ABC) as a technology for waste heat recovery (WHR) at the level of the preheater tower in a cement industry. An optimization code has been developed in MATLAB environment and linked with REFPROP database as a way to design and calculate the different parameters and points of the cycle. The theory of power maximization is adopted and the genetic algorithm is employedasa way to maximize the net power output of the cycle, while a case study of a real cement plant has been taken into consideration for the examination purpose. Results showed that the integration of the ABC cycle for energy valorization contributes to covering around 8.5% of the industry need for electrical energy, by generating an amount of power that can achieve 1.07 MW.In addition, although the cycle has shown a low efficiency, it can be a practical WHR solution especially in case of water deficiency.

NOMENCLATURE

p	Pressure, bar	*in*	Inlet
P	Power, kW	*out*	Outlet
T	Temperature, °C	*HE*	Heat exchanger
TI	Turbine inlet pressure	*t*	Turbine
r_p	Ratio	*c*	Compressor
Abbreviations		*p*	Polytrophic
ABC	Air bottoming cycle		
		Greek symbols	
Subscripts		η	Efficiency, %
Is	Isentropic	Δ	Difference

I. Introduction

Nowadays, energy valorization is categorized as a priority aspect, in order to reduce greenhouse gas emissions (GHG) and energy consumption. Cement industries are classified among the most energy-intensive industries[1], where a the production of a ton of clinker required an amount of energy ranges between 3.2 and 6.3 GJ [2,3],this besides that they are characterized by enormous discharge of waste heat that can achieve 40% of the imputed energy[4]. In the midst of this, researchers have developed various technologies aim to recover waste heat from the industrial sector, including steam and organic Rankine cycles[5], Kalina cycle[6], Air bottoming cycle[7], and also combined cycles[8], these technologies aim to recover the waste heat as a means tore-use it in the same (see e.g,[9]) or in other forms, such as the generation of the electricity.

In this framework, the examination of waste heat recovery at the level of the cement industries started several years ago too, where several researchers investigated different technologies and methods for this purpose. As an example, Khatima et al. [10] investigated the possibility of recuperating the tertiary as well as secondary air from the cooler in an Algerian cement industry, and they analysed its influence on the clinker production. They concluded that hot air recovery improved clinker production.In addition, Miroli et al. [11], introduced the Kalina cycle technology for industrial applications, then they summarized the application of this technology for waste heat recovery at the level of the cement industry, they mentioned that the use of Kalina cycle results in energy costs reduction, and it offers a performance improvement between 20% to about 40%, relative to conventional waste heat systems. In contrast, Legmann[12], drew the results of the use of the first ORC application in the cement industry, with a potential of 1.5 MW. Additional to power generation, he found that the use of this power plant results in a significant reduction of the annual CO_2 emissions, this reduction correlated to the electrical energy CO_2 emissions. As well as Karellas et al. [13], studied the possibility of waste heat recovery at the level of the cement plants, using the water stream cycle, and the organic Rankine cycle. For the ORC cycle, they used a medium cycle that works with the water as a thermal loop to conduct the heat from the source to the cycle, and they trapped their selection of working fluids in 4 candidates. In addition, they choose the recuperative configuration for the ORC. The results showed that the water stream cycle is more efficient in the high-temperature levels, which are more than 350°C.However, despite the diversity and the existence of many works in this field, at the time of writing and as the authors know, there is no work in the literature evaluated the waste heat recovery using Air bottoming cycles at the level of cement industries, although that this technology can be a feasible solution especially in case of water deficiency since the use of the air as working fluid allows no need to steam equipment such as the condenser, which results in a simple configuration and architecture, lower maintenance costs, and shorter start-up time [14].

Algeria is a leading country in cement production in North Africa, with a production rate capacity achieves40 million tons per year, through the exploitation of more than 17 industries in its different regions. This high production is associated with an enormous loss of energy in the form of waste heat at the different levels of these industries. Note that, there is no one of them uses the different technologies for waste heat recovery.

In this context, this work aims to study and investigate the air bottoming cycles from a thermodynamic point of view as a technology for waste heat recovery from cement industries, through the exploitation of the waste heat at the level of the preheater tower as a heat source for the cycle. To perform that, a real case study of a cement industry in the north of Algeria was taken into consideration.

This paper includes in its rest the following sections; the subsequent section is dedicated to the methodology, where the case study is described with its different parameters, the technology and the thermodynamic model, and also the optimization settings are presented. Then, the simulation results are outlined and discussed in the penultimate section, while the conclusion and the remarks are left for the last section.

II. Methodology

II.1. Case Study

In order to evaluate the adaptability and the applicability of the ABC at the level of the cement industries, a case study was selected presented in a cement industry in the North of Algeria. The investigation of the waste heat availability at its level revealed the presence of an enormous quantity of waste heat at the level of the preheater tower, in the form of exhaust gas with an average temperature that achieves 382 °C and an average mass flow rate of 47.113 kg/s. Figure 01 illustrates the waste heat source at the level of the preheater tower in this cement industry.

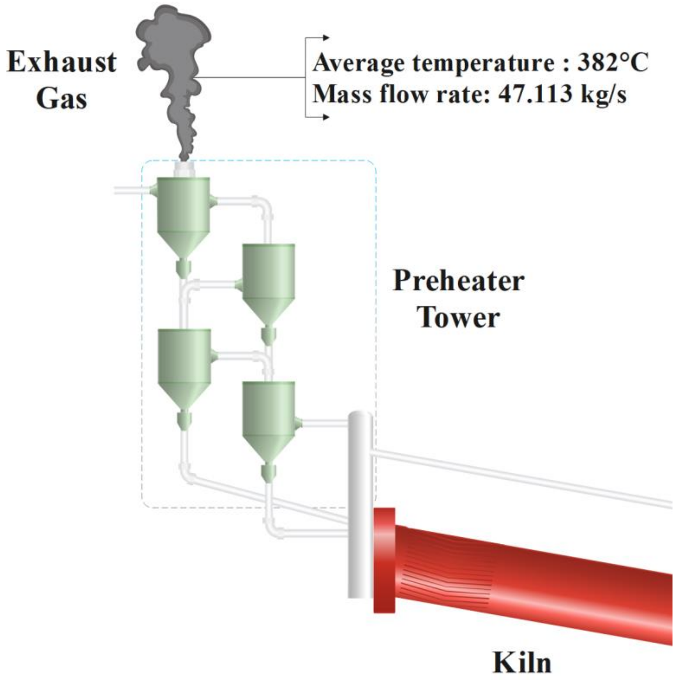

Figure1. Exhaust gas at the level of the preheater tower

II.2. Technology and thermodynamic Model

Air bottoming cycle technology appeared in 1988 at general electric, where Ferrell invented a new technology that replaced the steam cycles [15], and then at the end of 1988, Anderson and Ferrell patented this technology for coal gasification plant, where they used the coal fuel exhausts as heat source [16], after that, Wicks et al [17] introduced its theoretical concept.

In the air bottoming cycle, the air enters the compressor at atmospheric pressure, where its pressure increases, the compressed air is heated in a heat exchanger which ensures a heat transfer between the waste heat and the air before it follows through an air turbine, In the turbine, the air with high pressure and hot temperature expanded while shaft work is generated. Then, the air is exhausted to a stack and can be used for some other utilization. (see e.g[18]). Figure 2, present a schematic diagram of the basic air bottoming cycle.

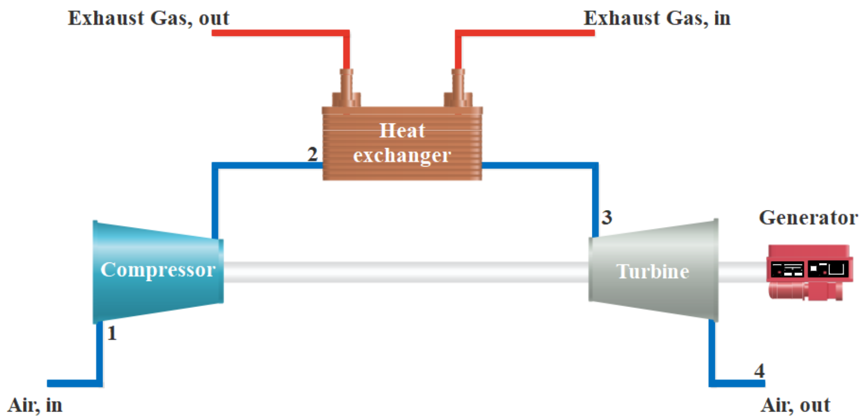

Figure 2. Air bottoming cycle scheme

The thermodynamic equations that are employed in order to calculate the different points and parameters are adopted from[18], and they are listed as follows:

The work of the compressor is calculated as:

$$W_c = \dot{m}(h_2 - h_1) \qquad (1)$$

While the heat added to the system is computed as follows:

$$Q_{HEX} = \dot{m}(h_3 - h_2) \quad (2)$$

On the other side, the work of the turbine is determined as:

$$W_t = \dot{m}(h_4 - h_3) \quad (3)$$

The Net power output of the cycle is estimated using equation (4)

$$W_{net} = W_t - W_c \quad (4)$$

The efficiency of the cycle is given as:

$$\eta = \frac{W_{net}}{Q_{HEX}} \quad (5)$$

Since this works aims to maximize the net power output of the cycle, the theory of optimum pressure ratio for maximum net power output is employed asproposed in[19], where the pressure ratio equation is given as follows:

$$r_p = \left[\left(\frac{T_3\,\eta_C \eta_t}{2\,T_1}\right) + \frac{1}{2}\right]^{\frac{\gamma}{\gamma-1}} \quad (6)$$

The compressor and turbine isentropic efficiencies are computed using the pressure drops and the polytropic efficiency according to [20] as:

$$\eta_{is,c} = \left(\frac{r_{p,c}^{\frac{(\gamma-1)}{\gamma}} - 1}{r_{p,c}^{\frac{(\gamma-1)}{\gamma\,\eta_{p,c}}} - 1}\right) \quad (7)$$

$$\eta_{is,t} = \left(\frac{r_{p,t}^{\frac{\eta_{p,t}(\gamma-1)}{\gamma}} - 1}{r_{p,t}^{\frac{(\gamma-1)}{\gamma}} - 1}\right) \quad (8)$$

II.3. Optimization settings and parametrization

An optimization code has been developed as a way to optimize and design the ABC cycle, this code is implemented in MATLAB environment and linked with REFPROP database [21]. The code uses the genetic algorithm provided in MATLAB toolboxes to determine the optimum parameters and calculate the different points according to the heat source type and by employing the equation listed in section II.2. Furthermore, it gives the hand to select and use a single or multi-objective optimization approach, as a way to optimize the desired parameters such as the net power output.

In this work, the design and the optimization of the ABC are performed using a single objective function aiming to maximize the net power output.For this purpose, the basic architecture is implemented in the code.The selection of this configuration was intending to reduce the plant costs and complexity. Figure 1 illustrates the configuration that is examined.

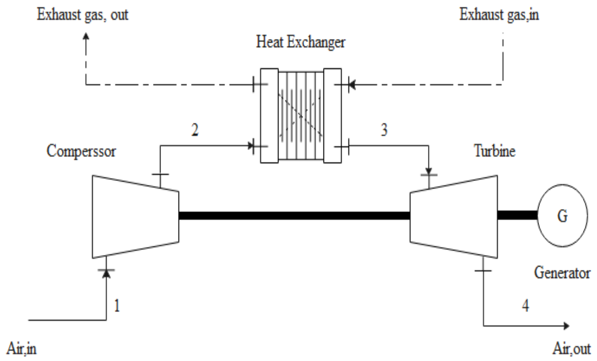

Figure 3. Basic configuration of Air Bottoming Cycle

The different parameters of the various devices of the cycle, and the upper and lower bounds (UB and LB) for the different variables are selected and assumed based on the authors' experience, the literature, and plant manufacturers' data and knowledge, and they are listed in Tables 1 and 2.

Table 1. Assumed parameters for the different equipment of the ABC

Parameter	**Value**
Compressor polytropic efficiency (-)	0.90
Turbine polytropic efficiency (-)	0.90
Compressor mechanical efficiency (-)	0.97
Turbine mechanical efficiency (-)	0.97
Electric generator efficiency (-)	0.98

Table 2. UB and LB used in the optimization of the ABC

Parameter	**LB**	**UB**
Heat source outlet temperature, $T_{Hot,out}$ (°C)	70	T_{hot}
Turbine Inlet Temperature, TIT (°C)	100	TIT_{max}
Minimum temperature difference in the Heat exchanger, $\Delta T_{pp,HE}$ (°C)	20	100

III. Results and Discussion

As mentioned before, a thermodynamic optimization aiming for maximizing the net power output is carried out, using the developed code which employs a single objective function. The pressure drop and the heat loss are assumed to be negligible, while the used parameters for the genetic algorithm are selected as follows:

- Number of generations: 200,
- Populations: 150,
- Crossover fraction: 0.8,
- Mutation fraction: 0.2.

The optimization outcomes of the mentioned case study are listed in Table 3.

Table 3. Design point results for the air bottoming cycle

Variable	**Value**
Pressure ratio p_2/p_1 (-)	2.93
Mass flow rate (kg/s)	48.89
Heat source outlet temperature, $T_{Hot,out}$ (°C)	165.85
Turbine Inlet Temperature, TIT (°C)	361.85
Pinch point in the Heat exchanger, $\Delta T_{pp,HE}$ (°C)	20.1
Compressor isentropic efficiency (-)	88.4
Turbine isentropic efficiency (-)	91.3
Net power output, P_{ABC} (MW)	1.07
Thermal efficiency (%)	9.7

The optimization results, using the theory of power maximization employing the equation (6) show that the cycle under the mentioned conditions can produce a quantity of power that achieves 1.07 MW, corresponding to an optimal pressure ratio of 2.93, and a thermal efficiency of 9.7%. On the other side, the isentropic efficiency of the compressor and turbine are computed by the solver using equations (7) and (8) results in an efficiency of 88.4% and 91.3% for the compressor and the turbine respectively. In addition, the optimum heat source outlet temperature, the mass flow rate, and the pinch point in the heat exchanger are 165.85 °C, 48.89 kg/s, and 20.1 °C respectively.

These obtained results mentioned that the implementation of an Air bottoming cycle at the level of the preheater tower of this cement industry can cover around 8.5% of the total electricity consumption in the industry, simultaneously, the cycle can produce around 25.68 MW a day, this quantity of power can cover around 25% of the industry need of electricity during the rush hours as the average consumption is around 12.5 MWh, which leads to the reduction of the electricity bills with about 30 %.

The design calculated points of the cycle are listed in table 4. While the T-S diagram and the pinch point position are shown in Figure 4.

Table 4. Design point results for the ABC

Point	T (°C)	s (J/kg/K)	p (bar)	h (kJ/kg)
1	25.00	6860.41	1.01	298.447
2	145.80	6894.75	2.97	420.341
3	361.85	7325.51	2.97	644.442
4	213.09	7356.28	1.01	489.294

(a) (b)

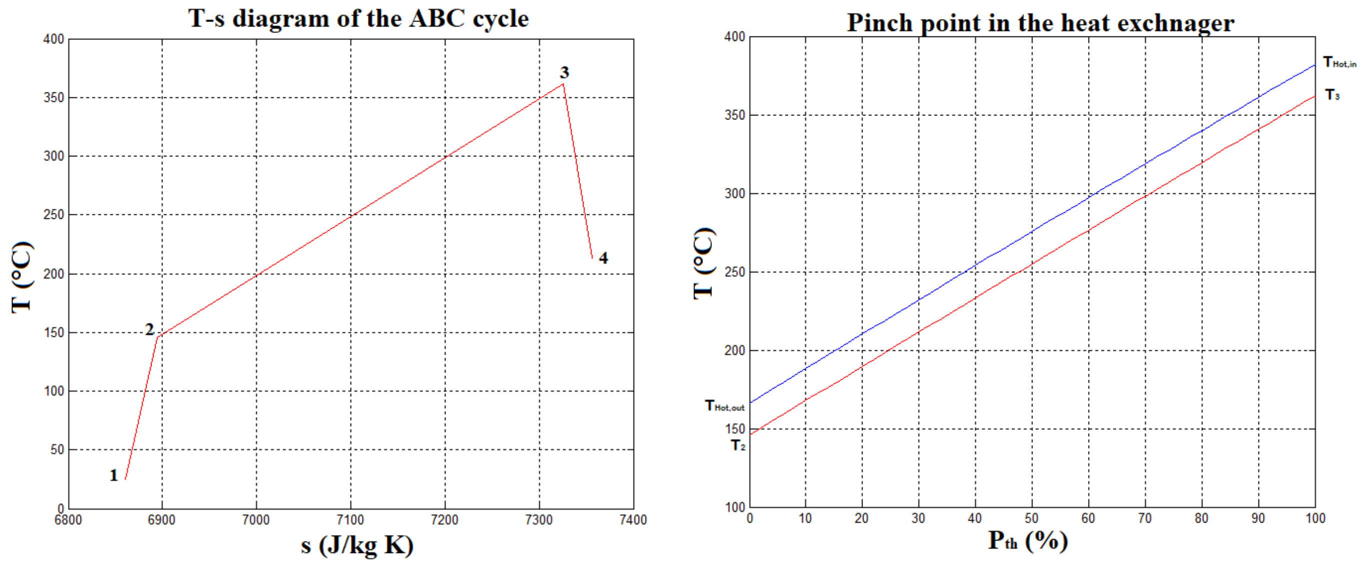

Figure 4. (a). T-S diagram of the ABC, (b). The pinch point in the heat exchanger

Therefore, although that the ABC cycle is characterized by a low efficiency compared to other technologies, but it can be considered a feasible solution for waste heat recovery at the level of preheater tower in this the cement industry, especially in case of water deficiency, and also in the case of a high-temperature waste heat source, which can lead to better performance of the cycle. In addition, this solution can be generalized for the WHR purpose at the level of the Algerian cement industries, since most of them use the same production process and fuel, and work under the same conditions.

IV. Conclusion

Algeria is a leader country in cement production in north Africa, with a production capacity achieves 40 million tons per year. this massive production is associated with large heat losses and enormous GHG emissions.

So, as a way to reduce these emissions and recover the waste heat, the authors proposed the integration of an ABC cycle as a possible solution to this purpose. Then, as a means to study, design, and optimize this technology, an optimization code has been developed, through the employ of the genetic algorithm available in MATLAB toolboxes in accordance with the REFPROP database to determinate the different points and parameters of the cycle. In addition, a real case study has been selected for this purpose.

The examination of the air bottoming cycle for waste heat recovery at the level of the selected cement industry revealed that it can cover around 8.5% of the total needs of electricity, and can cover around 25% of the total need of electricity during the rush hours, this proves that the implementation of this technology has a positive effect on the energy consumption by recovering the waste heat from the industry, which is one of the major aspects nowadays.

Therefore, the simulation outcomes show that the integration of an air bottoming cycle for waste heat recovery at the level of preheater tower in this cement industry is favorable from a thermodynamic and environmental point of view, as it contributes to the reduction of both energy consumption and greenhouse gas emissions which are associated to the generation of the consumed electricity.

References

[1] Engin T, Ari V. Energy auditing and recovery for dry type cement rotary kiln systems - A case study. Energy Convers Manag 2005;46:551–62. https://doi.org/10.1016/j.enconman.2004.04.007.

[2] Van Oss HG, Padovani AC. Cement manufacture and the environment - Part I: Chemistry and technology. J Ind Ecol 2002. https://doi.org/10.1162/108819802320971650.

[3] Van Oss HG, Padovani AC. Cement manufacture and the environment, Part II: Environmental challenges and opportunities. J Ind Ecol 2003. https://doi.org/10.1162/108819803766729212.

[4] Kabir G, Abubakar AI, El-Nafaty UA. Energy audit and conservation opportunities for pyroprocessing unit of a typical dry process cement plant. Energy 2010;35:1237–43. https://doi.org/10.1016/j.energy.2009.11.003.

[5] Zhang X, Wu L, Wang X, Ju G. Comparative study of waste heat steam SRC, ORC and S-ORC power generation systems in medium-low temperature. Appl Therm Eng 2016. https://doi.org/10.1016/j.applthermaleng.2016.06.108.

[6] Zhang X, He M, Zhang Y. A review of research on the Kalina cycle. Renew Sustain Energy Rev 2012. https://doi.org/10.1016/j.rser.2012.05.040.

[7] Pierobon L, Haglind F. Design and optimization of air bottoming cycles for waste heat recovery in off-shore platforms. Appl Energy 2014. https://doi.org/10.1016/j.apenergy.2013.12.026.

[8] He M, Zhang X, Zeng K, Gao K. A combined thermodynamic cycle used for waste heat recovery of internal combustion engine. Energy 2011. https://doi.org/10.1016/j.energy.2011.10.014.

[9] Redjeb Y, Kaabeche-djerafi K, Saouli O. AspenPlus based simulation for waste heat recovery in cement industries. J New Technol Mater 2019;08:82–6.

[10] Kaabeche-Djerafi K, Kara M, Ghernoug S, Belbaki A, Bousba S. Energy recovery in the baking line of the cement plant djawad taher of algeria. Chem Eng Trans 2014;37:739–44. https://doi.org/10.3303/CET1437124.

[11] Mirolli MD. The Kalina cycle for cement kiln waste heat recovery power plants. 2005 IEEE Cem Ind Tech Conf Rec 2005;2005:330–6. https://doi.org/10.1109/CITCON.2005.1516374.

[12] Legmann H. Recovery of industrial heat in the cement industry by means of the ORC process. IEEE Cem Ind Tech Conf 2002:29–35. https://doi.org/10.1109/CITCON.2002.1006482.

[13] Karellas S, Leontaritis AD, Panousis G, Bellos E, Kakaras E. Energetic and exergetic analysis of waste heat recovery systems in the cement industry. Energy 2013;58:147–56. https://doi.org/10.1016/j.energy.2013.03.097.

[14] Korobitsyn M. Industrial applications of the air bottoming cycle. Energy Convers. Manag., 2002. https://doi.org/10.1016/S0196-8904(02)00017-1.

[15] Farrell WM. Air cycle thermodynamic conversion system. US4751814A, 1988.

[16] Alderson ED, Farrell WM. Air bottoming cycle for coal gasification plant. 4785621, 1988.

[17] Wicks F. Thermodynamic theory and design of an ideal fuel burning engine. Proc. Intersoc. Energy Convers. Eng. Conf., vol. 2, 1991.

[18] Hånde B, Førde M. Air bottoming cycle: Use of gas turbine waste heat for power generation. J Eng Gas Turbines Power 1996. https://doi.org/10.1115/1.2816597.

[19] Boyce MP. Gas Turbine Engineering Handbook. 2012. https://doi.org/10.1016/C2009-0-64242-2.

[20] Ghojel J. Fundamentals of Heat Engines: Reciprocating and Gas Turbine Internal Combustion Engines. Wiley; 2020. https://doi.org/10.1002/9781119548829.

[21] Lemmon EW, Huber ML, Mclinden MO. REFPROP 9.1. NIST Stand Ref Database 2013.