WHR and CHP Processes in Cement Industry, New Techniques Based on Kalina's Cycle

Krzysztof Jesionek, Jerzy Duda

Abstract: *Cement production is a power-consuming process. The experience confirm that usage of alternative fuel in cement industry is the safe method of wastes' utilization, environmentally friendly and profitable for plants and society. Still better solution is connection of WHR (Waste Heat Recovery) and CHP (Combined Heat and Power) systems. The method refers to problems mentioned above and presented in the paper.*

Key words: *Waste Heat Recovery, Combined Heat and Power, New Techniques, Cement Industry.*

INTRODUCTION

Aiming to lower energy-consumption and to limit unrenewable-fossil fuels consumption stems not only from the progressive growth of energy process but also from the necessity of improving work conditions and also limiting harmful industry influence on environment and to make it right with the emission standard of UE countries defined in BREF **(**BAT Reference Document). Practically, thanks to usage of multistage heat exchangers and the process of preliminary calcination, the limit of possibilities of further lowering heat consumption in the process of clinker burning, through the devices' construction optimalization has been achieved. As it stems from the Sankey's graph – Fig. 1, heat balance of typical cement kiln working in dry method regime – the main thermal losses make up approx. 30 % and this is the enthalpy of outlet gases and excess air from the clinker cooler.

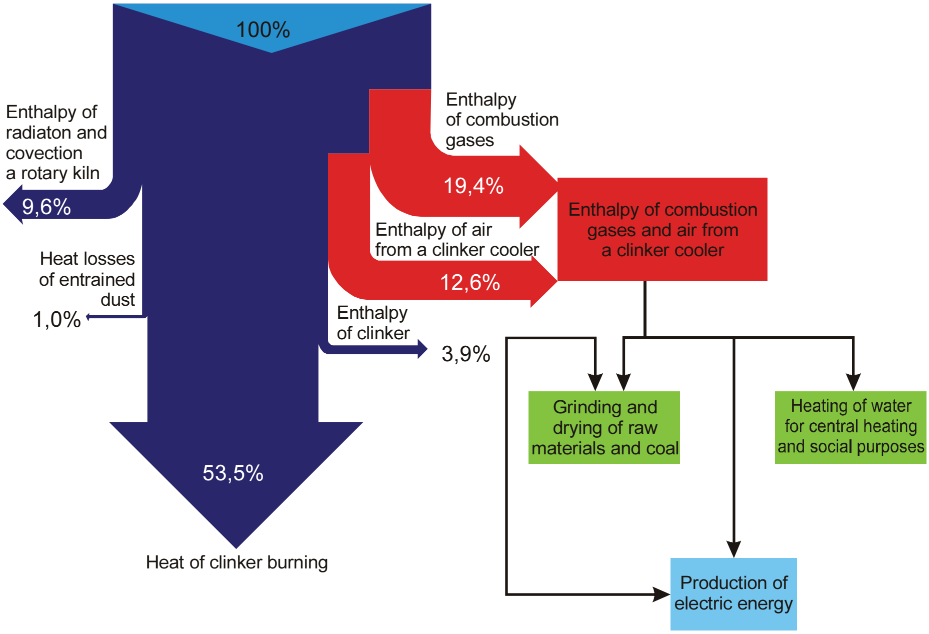

Fig. 1. Cement kiln energy balance and methods of waste-heat usage

Chance to improve energy efficiency of burning process is using waste enthalpy of that process. One of the management methods of this enthalpy is using it to dry raw materials and fuel which are used during cement production process. On the ground of the growth of the cement kiln efficiency and stemming from that growth of waste heat, this process is very often not sufficient. In connection to that there are researches conducted on the other methods of waste enthalpy utilization. Most often it is used for hot water production and water steam for both heating and social purposes. Heat production for heating and social purposes was found of no interest in Poland. It is because distances from cement plants to housing estates are long and costs of transfer is high. In connection to that, it seems that at present level of technology, using waste heat for electrical energy is one of the practical methods of using enthalpy, [1]÷[6].

NEW TECHNIQUES FOR THE PRODUCTION OF ELECTRICITY

Aiming to lower energy-consumption and to limit unrenewable-fossil fuels consumption. The relatively low temperature of exhaust gases (about 620 K), the large variability of redundant air enthalpy from coolers (large temperature fluctuations) and the required thermal energy in the drying process, require a different technology than the classic Rankine cycle – how to generate electricity from waste of enthalpy. Therefore, the current task is to search for other techniques based on the Rankine cycle, which can operate at lower temperaturesthe waste heat of large load changes. One way is to replace the working medium – water, other liquids, which has a lower boiling point and a lower enthalpy of vaporization. Such liquids are e.g. organic liquids such as isopentane or isobutane type. WHR plants with an organic working medium, whose principle of working is based on the classic Rankine cycles, are defined as the ORC (Organic Rankine Cycle).

ORC cycle is a dual-circulation system. One circulation creates indirect factor – heating (e.g. thermooil), while the second primary circuit forms a working medium – organic fluid. Dual-circuit system is used for the safety of the installation ORC. Process waste heat – enthalpy exhaust gases and/or exswss air from the clinker cooler – heats in regenerative boiler the intermediate factor, it is mostly thermooil (silicone oil). Then hot thermooil is used in the evaporator to produce steam from the organic fluid, which drives a turbine coupled to a generator.

Swiss company ABB in their ORC systems use as an indirect factor high pressure water of the order of 18÷22 bar [7]. The advantage of this technology is lower operating costs and lower power consumption for own needs of the ORC. Thermooil at any given temperature ranges characterized by almost 2 times less thermal capacity than water and higher viscosity (larger hydraulic resistance). The result of that is higher (about 35 %) power consumption of the pump thermooil in relation to the energy consumption of the water circulation pump. An important feature of water is also thermodynamic stability of its parameters. However, thermooil parameters change during the operation, which requires frequent (in peroid about 2 years) exchange and associated with that additional costs.

A similar solution to the ORC – also based on the Rankine's cycle – is a Kalina cycle, which was invented in Russia in 1967 by Alexander Kalina and was first used in Paratunka (Kamchatka). Fundamental difference in Kalina cycle in relation to the ORC cycle consists of changing working medium. In the Kalina cycle in a place of organic liquid is used two-component mixture (water and ammonia) so-called binary system. The boiling temperature of the mixture NH_3/H_2O depends on the proportion of the water and ammonia. Figure 2 shows the effect on the concentration of ammonia in the mixture of the Kalina process.

The data shows that the higher content in the mixture of ammonia, the lower the temperature of evaporation and condensation. To get more power, the pressure drop should be large. Therefore, the aim is to obtain a high pressure at the inlet to the turbine and the low pressure in the condenser. Thanks to the fact that the working medium is a mixture of two phases differing boiling temperatures of each component can be varied thermodynamic parameters of the steam and condensate.

In the Kalina cycle, at a given temperature heat source and set up temperature difference (steam-condensate), it is possible to change the pressure by changing the concentration of ammonia. For example, lowering the pressure in the condenser can be achieved by reducing the concentration of ammonia in the condensate, which allows the supply of (low in ammonia) liquid from separator. The graph in Fig. 2 shows also high sensitivity of the cycle to small changes in concentration of ammonia. This concerns particularly the scope of high concentration, where there is a large concentration of isobars. Small changes in the participation of ammonia cause large pressure changes, [8].

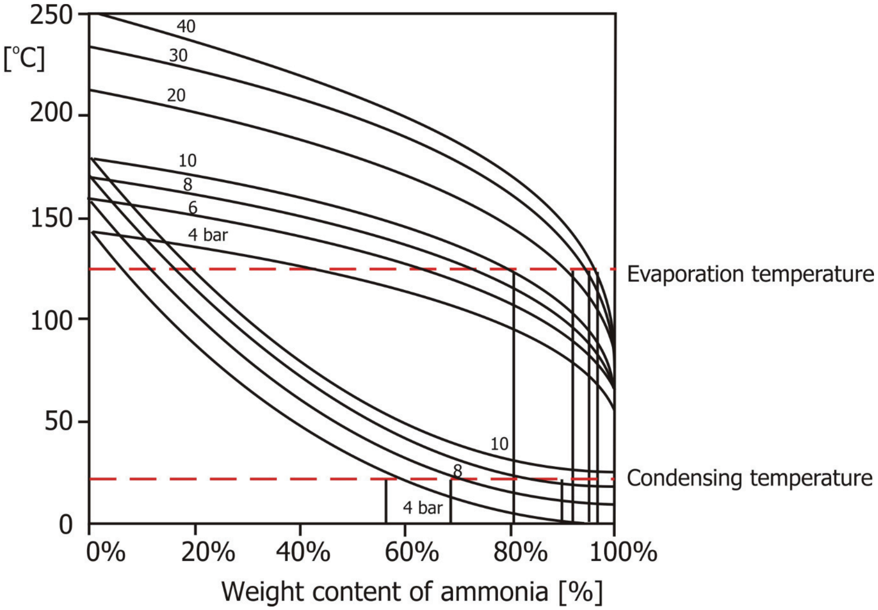

Fig. 2. Effect of ammonia concentration on the thermodynamic parameters of steam and condensate [8]

Typically this proportion shall be 70 % of the ammonia and 30 % water. A mixture of (NH_3/H_2O) with ratio of a homogeneous liquid – water boiling over a wide temperature range, so that the amount of energy recovered from waste heat stream is significantly (about 15÷25 %) higher compared with the water. The choice of aspect ratio of ammonia-water factors, allows to adjust to the temperature of waste heat sources.

Kalina cycle is increasingly used technique to utilise waste heat to generate electricity. Like ORC cycle is used for low and medium temperatures of waste heat (400÷700 K). The similarity between the ORC and Kalina cycle results in the fact that they are the solution coming from the classical Clausius-Rankine's cycle. An important advantage of ORC and Kalina's cycle – particularly in systems cooperating with the rotary boiler, where large enthalpy of the excess air changes can be expected – is being less sensitive to changes in load than in classical C-R cycle which is very sensitive to these changes. For comparison, the two circuits in Fig. 3 shows an example of ORC and Kalina's cycle working in parallel on a single source of waste heat.

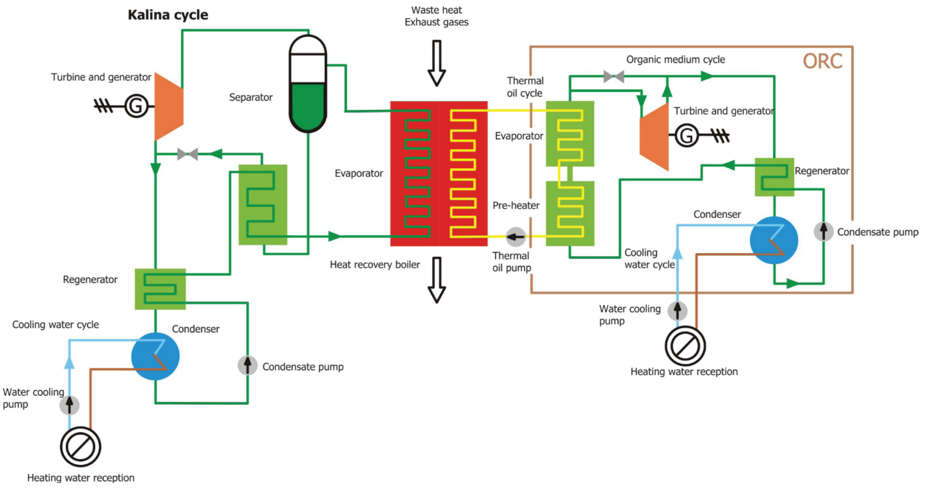

Fig. 3. Schema of Kalina and ORC cycle

As a result, of supplying the heat (enthalpy gases) to waste-heat boiler in Kalina's cycle is evaporation of the medium – the mixture (water and ammonia). Then, in the separator from the vapor phase the steam is being extracted with a high content of ammonia, which drives the turbine. However, the aqueous phase from the separator flows through a heat exchanger and then mixed with the expanded ammonia steam in the turbine. Established mix of steam and water is fed through the recuperator to the capacitor (condensator). The condensate is pumped by circulating pump through the heat regenerator, reheater and then to the boiler proper.

From the comparison shown in Fig. 3 two cycle are different only in working medium used and in the ORC cycle by intermediate heating unit installed. In both the ORC and Kalina's cycle after going though turbine the expanded steam before being lead to the condenser flows through the recuperator where initially preheats the condensate. The Kalina's cycle, the ratio of ammonia to the water is changed depending on the process occurring in the cycle, and it is not constant while all thermodynamic process taking place in it. Additionally Kalina's cycle due to the binary working medium must be equipped with vapor separator. However, in ORC systems separator is used only in exceptional cases where due to the parameters of the heat source and the organic medium may result in the occurrence of a drops of liquid in steam

SELECTING THE BEST SOLUTION

As can be seen from the experience on domestic and foreign field and cost analysis the best solution for waste heat sources with temperatures above 650 K is a classic Clausius-Rankine's cycle. However, the so-called low-temperature sources (below 600 K) the OCR or Kalina's cycle is recommended which have lower boiling working medium point. Table 1 shows some chosen biggest available sources of enthalpy waste of rotary kilns working in the Poland.

Having regard to the average content of water (7÷9 %) in domestic natural raw materials for the production of cement and the consequent required minimum drying gas temperature of about 540 K for the heat source available for use will be a lower enthalpy than those shown in table 1. Therefore, to further assess the WHR choice is limited only to the low-temperature systems like ORC and Kalina.

In comparison to the classical Clausius-Rankine's cycle and organic ORC, Kalina's cycle is characterized by significantly improved efficiencies. This is due to the difference of thermodynamic processes in the Kalina cycle over the Rankines cycle processes.

Classical Rankine cycle and ORC consists includes isobar-isothermal transformation in boiler proper and isobar-isothermal condensing the expanded steam. However, in the Kalina cycle is used non-isothermal process of evaporation and condensation of the mixture. Assuming heat losses in heat recovery boiler, turbine and condenser identical for all systems, than the efficiency of Kalina's cycle will be 15÷25 % higher than comparable in Rankine's cycles. Similar in favor of the Kalina's cycle, compared with ORC are as installation costs and the potential capacity to produce electricity. In Figures 4 and 5 a comparison of ORC and Kalina's cycle is shown in terms of cost and power generation, depending on the temperature of the available waste heat sources.

Tab. 1. Some biggest available sources of enthalpy waste of rotary kilns in Poland

Cement factory	Enthalpy of combustion gases	Enthalpy of excess air	Combustion gases parameters		Excess air parameters	
	KJ/kgK	KJ/kgK	m^3_n/kgK	Temperature, K	m^3_n/kgK	Temperature, K
I	800,79	371,78	1,43	656	1,23	520
II	801,60	231,30	1,59	615	–	–
III	641,31	411,81	1,46	630	1,15	560
IV	777,80	427,09	1,49	635	1,31	540
V	857,47	198,50	1,55	635	0,68	560

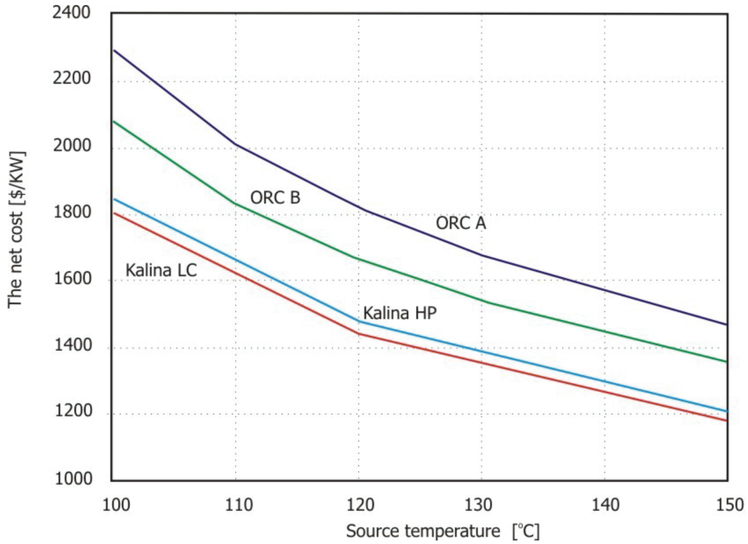

Fig. 4. Compare of costs of Kalina and ORC cycles, depending on the heat source temperature, [9]

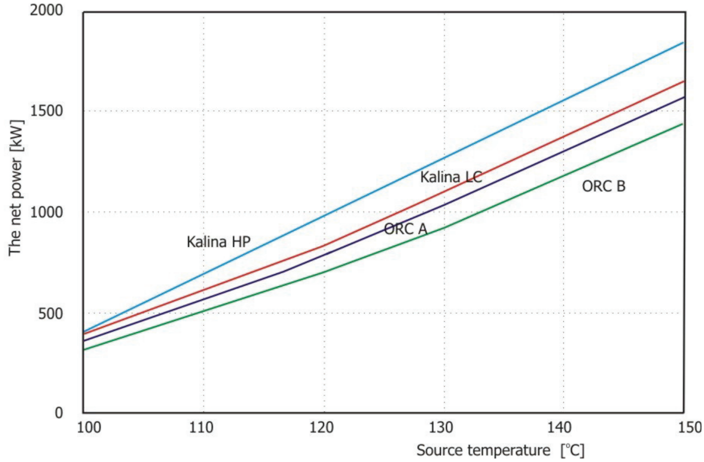

Fig. 5. Compare of energy power of Kalina and ORC cycles, depending on the heat source temperature, [9]

We compared two different ORC systems (A and B) with two Kalina's systems. ORC A system characterized by the high cost of energy and power produced. However, ORC B, was low cost and low power system. Similarly, "Kalina LC" is a low-cost system and "Kalina HP" is a system of high-power and cost. Both the cost of energy and the volume in each case of Kalina's system was favorable and proved to be more beneficial than in ORC's one.

In recent years there has been rapid development of Kalina's techniques, that applies to both system solutions and utilization possibilities. The development is due to the larger theoretical possibility of using Kalina cycle and improved operating rates especially with the use of low temperature waste energy. For example, in the diagram Fig. 6 shows the heat rates of electricity generated from geothermal sources for different solutions in ORC and Kalina cycles.

The presented data show that the solutions based on the Kalina cycle characterized by better indicators than ORC. Kalina technology despite its advantages has not yet found application which, as in the initial period of ORC was mainly limited to a few geothermal sites (in Japan, USA, Germany and Iceland). The Kalina technology development and increasing its use provides high interest not only by the leading companies in the energy sector but also by the companies specialized in the production of equipment to other technologies. An example is the Danish company FLSmidth manufacturer of machinery and equipment for cement plants that purchased a license Kalina cycle. In 2012, FLS will start his first installation WHR (Khairpur Kalina Cycle) with a capacity of 8.6 MW in the Khairpur Cement Plant (Pakistan).

So far little interest in Kalina systems is due to the relatively short time since the launch of the first installation and the lack of more operational experience. It is still being developed - prototype technology therefore, it seems that the ORC system is the best solution for the cement plant. The ORC system supports a large number of a successful installations, and diversity of application. It's tested and safe to use. An important advantage is a relatively simple system that allowed the installation of modular construction.

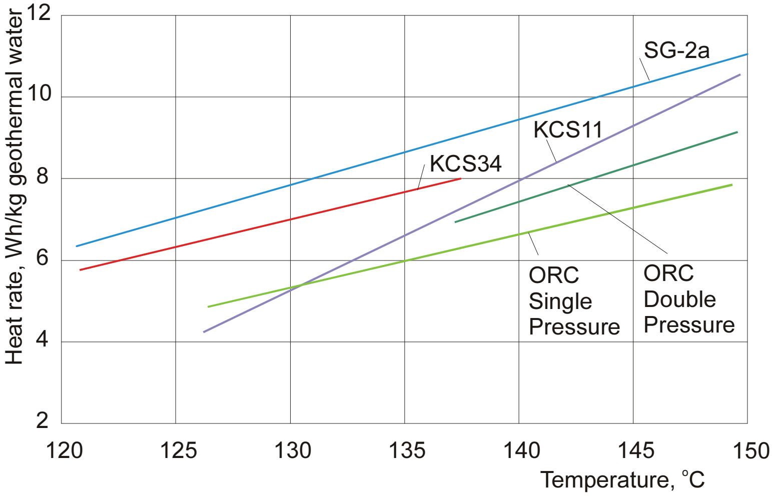

Fig. 6. Effect of the heat source temperature and operation system on heat rates of electricity generated

However, the Kalina cycle is still at the stage of updating and development as ORC was 30 years ago. On the one hand, the possibility of variation in the ratio ammonia/water during the process can be adapted to the existing conditions in the cycle. On the other hand, the system is operationally difficult. The big problem is the efficiency of separation system (maximum limit of water part in the ammonia steam) and mixing the expanded steam with a solution of water from the separator. Separation and mixing quality has a major impact on the stability of the process and the life of the turbine. Steam with higher water content can caused hydro-mechanical damage of the turbine blades. In addition, chemical properties of ammonia create a serious meance in corrosions for the installation which must be made of high quality stainless steel.

SUMMARY

The combination of burning process with the installation for the production of electricity is now one of the major steps in line with the climate and energy package 3x20. The development of new techniques for the production of electricity is capable of producing clean electricity from the waste heat of the cement production process. Having previous experience with operating systems ORC and Kalina and work done on model testing new solutions in Kalina's cycle, can be concluded that they are future-oriented solutions for the cement industry. Kalina's cycle that characterizes the best efficiencies can be (after elimination of the current difficulties) the primary system for cement plants. This technology is now at a similar level of development as ORC 30 years ago, when it also due to the lack of experience and references - it was difficult to find companies willing to implement. In practical, almost until the end of the twentieth century (after about 50 years since the first attempts to apply) ORC systems are widely used. Implementation and propagation of Kalina's cycle will certainly be faster due to the strong similarity and experience gained from the operation of the ORC system.

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ABOUT THE AUTHORS

Prof. Krzysztof Jesionek, DSc, PhD, Eng., Department of Boilers and Turbines, Faculty of Mechanical and Power Engineering, Wroclaw University of Technology, Phone: +48 71 3441207, E-mail: krzysztof.jesionek@pwr.wroc.pl

Prof. Jerzy Duda, DSc, PhD, Eng., Department of Technology and Work Environment Engineering, Faculty of Production Engineering and Logistic, Opole University of Technology, Phone: +48 77 4498000, E-mail: j.duda@po.opole.pl

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