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Examination of a Cement Plant's Use of A Kalina Cycle For Waste Heat Recovery

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Abstract *- The RAMCO Cements Ltd. Jaggaiahpet, cement industry used the Kalina cycles to cogenerate power from waste heat recovery. We looked into cement companies that could produce 4.6–4.8 million TPA of clinker per day. The Kalina cycle was thermodynamically modelled using equipment costs, heat transfer for the cycle heat exchangers, mass, energy, and entropy balances. The models were created using the Engineering Equations Solver and then genetically tuned. The net power generated and the specific investment cost was the optimization's objective functions. The thermodynamic modelling results demonstrated which cycle parameters affect the goal functions as independent variables, enabling the definition of their boundaries. It was also noted that an accurate assessment of the system's expenses is contingent upon the appropriate choice of turbine and the appropriate sizing of cycle heat exchangers, particularly those comprising the heat recovery steam generator. We were able to determine that a thorough analysis of the Kalina cycle configuration should be conducted by performing the cycle based on the optimization results. The cement industry can recover waste heat through the use of the kalina cycle. With a daily capacity of at least 4350 T/d, this cycle appears more promising in terms of net electricity generation; for smaller capacities, the Kalina cycle is more intriguing.*
Keywords: *Kalina cycle, waste heat recovery, ammonia-water mixture, Cement industry, heat loss, Cogeneration.*

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I.INTRODUCTION

There are several well-established and commercially successful waste heat recoveries (WHR) power systems available for the cement industry, ranging from traditional steam-based Rankine-cycle installations to WHR power systems based on the Organic Rankine Cycle (ORC) and Kalina cycle. According to IIP and IFC (2014), there are around 850 WHR power projects using Rankine-cycle steam-based technology worldwide, with the majority of them located in Asia. We concentrate our research on this WHR technology because, despite its relative lack of exploration, studies indicate that the Kalina cycle is more efficient than the other technologies described. It is essential to do study on the Kalina cycle for the cement sector in order to look at potential threats to the practicality of using this technology. . In this sense, it is important to develop research with key points such as the size of the plant and equipment, the capital cost of equipment and installation works, exhaust gas characteristics, industrial electricity tariffs, the reliability of power supplied, and environmental aspects among others. By the aforementioned, this article aims to evaluate the Kalina cycle performance for WHR and generation of electricity from the exhaust gases of the cyclone preheater of the rotary kiln, as shown in Figure 1 (Sullivan, 2012). The study based on a Brazilian cement factory with a daily production capacity of 2.1 thousand tons clinker, doing its optimization regarding net power, thermal and exergetic efficiency, and specific electricity generation cost. It is important to highlight that there are cement-manufacturing processes in which the thermal energy of the air can still use at the exit of the clinker cooler, but this study does not consider this possibility.

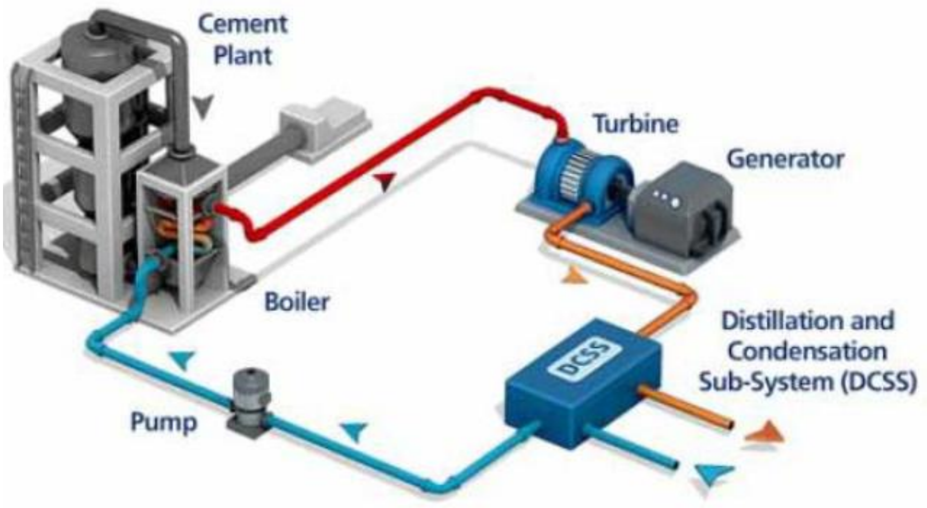

Figure 1: WHR for electricity generation with Kalina cycle in cement industry.

The Kalina cycle since it was patented in the 1980s has been studied for several applications of power generation from various thermal sources, among them the energy recovery of exhaust gases. As can be seen below, most of the studies on the Kalina cycle found in the literature deal with performance comparisons with other power cycles, such as organic Rankine cycle, for example, and related that Kalina cycle has higher thermal efficiency and lower specific investment or generation cost. The conventional steam cycle is the most common cycle for WHR power generation in cement industry, but ORC and Kalina cycle can be used to generate power from the waste heat of the chimneys of the cement factory. ORC is very similar to the steam cycle except that it uses an organic fluid. The fluid of the Kalina cycle is a combination of water and ammonia. The efficiency of the Kalina cycle is high (Amiri Rad & Mohammadi, 2018). In cement industry, the results of WHR with Kalina cycle indicated that the thermal and exergetic efficiencies range from 7-10% and 15-18% respectively. Those values are lower than the one presented by organic (ORC) and organic flash cycles (OFC) (Varma & Srinivas, 2017). A study involving heat recovery in sources at different temperatures shows that at temperatures higher than 180°C, the Kalina Cycle presented better performance than ORC (Y. Wang, Tang, Wang, & Feng, 2017). For thermal source temperature between 135 and 200°C the Kalina cycle shows higher thermal efficiency than Rankine cycle (Lin, Zhu, & Li, 2015). For WHR at temperatures up to 473 K Kalina cycle displayed a thermal efficiency of 26.32% (Sadeghi, Saffari, & Bahadormanesh, 2015). At the same boundary conditions the use of ammonia-water Kalina cycle for power generation from low-temperature heat sources could lead to a significant increase (25%) in efficiency over an organic Rankine cycle (Mergner & Weimer, 2015). A Kalina cycle for heat recovery at 300°C and cooling water at 25°C, shows a thermal and exergy efficiency 21.6% and 48.32%, respectively (Hua, Li, Chen, Zhao, & Li, 2015). For temperatures of the heat source and reference environment of 400°C and 25°C, respectively, Kalina cycle reaches 26.4% of energy recovery efficiency with a thermal efficiency of up to 27.02% (Zhu, Zhang, Chen, & Wu, 2016). A modified Kalina cycle for the utilization of low or medium temperature residual heat shows an energy recovery efficiency of 15.87%, close to 40% higher than the Rankine cycle efficiency (Hua, Chen, Wang, & Roskilly, 2014). The use of alcohol/alcohol mixture in substitution for the water-ammonia mixture proposed initially for the Kalina cycle the second law efficiency of around 55% when the residual heat has a temperature of 375°C (T. Eller, Heberle, & Brüggemann, 2017).

For medium temperature geothermal energy sources (98 to 162ºC) the Kalina cycle performed better efficiency than other evaluated cycles, achieving the energy efficiency of 10.6% and exergetic efficiency of 59.3% (Coskun, Bolatturk, & Kanoglu, 2014). For a geothermal energy source the Kalina cycle shows higher efficiency value than different thermal schemes of Rankine cycles and ORC (Jianyong Wang, Wang, Dai, & Zhao, 2015).

The Kalina cycle for heat recovery from a geothermal source at 200°C shows thermal efficiency of 17.06% and a geothermal energy recovery efficiency of 87.33% (Wei, Meng, Du, & Yang, 2015). In a solar-powered Kalina cycle and a geothermal system to generate superheated steam at temperature range 100-130°C at the turbine inlet indicated that the highest energy efficiency of the cycle (8.3%) achieved with a 95% ammonia fraction (Lolos & Rogdakis, 2009). With steam at 100 bar and 500 K at the turbine inlet in a solar thermal power plant Kalina cycle exhibited 31.47% of thermal efficiency (Modi & Haglind, 2015). The use of solar energy as source in a Kalina cycle shows that the energy efficiency of the optimized system is 8.54% (Jiangfeng Wang, Yan, Zhou, & Dai, 2013). At low-temperature residual heat (407.3 K) from a coal-fired

Rankine cycle steam plant Kalina cycle displayed net generation of 605.48 kW with 12.95% of thermal efficiency (Singh & Kaushik, 2013). In a refinery WHR application the Kalina cycle showed a higher power generation than ORC reaching a level of 996 kW with an efficiency of 10.57%, operating with an ammonia-water mixture of 70% (Varga & Palotai, 2017). In an integrated Kalina-Rankine ammonia-water cycle (AWKRC) application, the Kalina cycle was more efficient in electricity generation than Rankine, 17.38% versus 13.08% (Zhang, Guo, Chen, Wu, & Hua, 2015). From marine diesel engine exhaust gases (346ºC and 35 kg/s) as a heat source, the split Kalina cycle exhibited higher exergy efficiency (Nguyen, Knudsen, Larsen, & Haglind, 2014). The exergetic efficiency of the integrated compressed air energy storage system (CAES) and a Kalina cycle (KCS6) reached the 46% level (Zhao, Wang, & Dai, 2015). Kalina cycle systems with a two-phase expander to substitute a throttle valve (steam at 400 K) for power generation exhibited thermal and exergetic efficiencies ranged 7.97-10.51% and 39.40-52%, respectively (He et al., 2014). From biomass combustion and using a regenerative heater Kalina cycle presented the higher power generation and thermal efficiency (Cao, Wang, & Dai, 2014). Although the research agrees that the Kalina cycle is highly efficient, some applications show that other cycles have a higher performance than Kalina's. The double pressure ORC presented higher generation potential than Kalina cycle in geothermal plants for electricity generation (Shokati, Ranjbar, & Yari, 2015). In an evaluation of the electric power generation potential through a geothermal source in the Republic of Croatia with an average temperature of 175ºC the thermal and exergetic efficiency of the ORC reached 14.1% and 52% against 10.6% and 44% of the Kalina cycle, respectively (Guzović, Lončar, & Ferdelji, 2010). For geothermal heat sources (100-150°C) transcritical and subcritical ORC exhibit better performance than Kalina cycle (Walraven, Laenen, & D'Haeseleer, 2013). The Transcritical ORC exposed higher overall efficiency and lowered operating pressure compared to the Kalina cycle using the exhaust gas energy from an internal combustion engine (Yue, Han, Pu, & He, 2015). In all heat source temperature ranged between 200°C and 400°C the ORC with zeotropic mixtures obtained greater exergetic efficiency than Kalina cycle (Tim Eller, Heberle, & Brüggemann, 2017a). For heat recovery from a hybrid system SOFC / TG (Solid Oxide Fuel Cell / Gas Turbine) the optimum exergetic efficiency of the ORC was 62.35% versus 59.53% of the Kalina cycle (Gholamian & Zare, 2016).

II.METHODOLGY

This section explains the Kalina cycle, which was used to calculate the potential energy output from the exhaust gases of the rotary kiln's cyclonic preheater in a cement factory that can produce 4.685 Million TPA of clinker per day. In addition, we outline the cost, optimization, and thermodynamic models used to analyse cycle behaviour. These models were created in the EES to facilitate the completion of the computations. The factors taken into account to optimize the Kalina cycle's performance in terms of energy production, thermal and exergetic efficiency, and generation cost are displayed. The Kalina cycle from the exhaust gases of the cyclonic preheater of the cement industry's rotary kiln is shown in Figure 2 for WHR purposes.

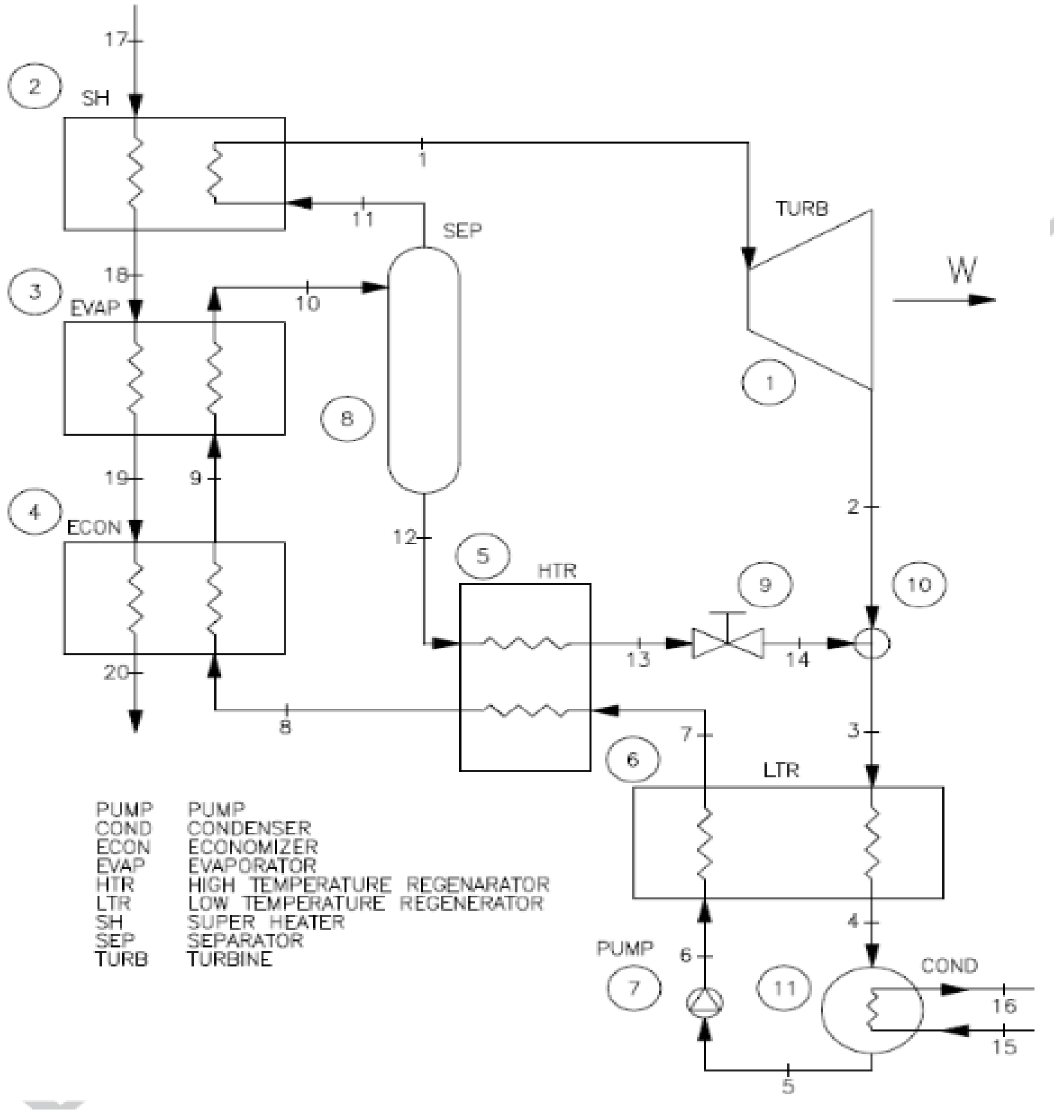

Figure 2: Kalina cycle developed in EES for WHR in cement industry

2.1 Kalina cycle description

The Kalina cycle, which is investigated for the thermal energy recovery of exhaust gases from the cyclonic preheater of the cement industry's rotary kiln, is depicted in Figure 2. The cycle's fluid is heated in the ECON (economizer) and evaporated in the EVAP (evaporator) (3). After the ammonia concentration is raised in the separator (SEP 8) the fluid is superheated in the super heater (SH 2). To provide mechanical power, the superheated steam expands through the turbine, or TURB (1). In the valve (9) from the SEP (8), the turbine's exhaust steam is collected and combined with the depressurized ammonia-poor liquid. By rejecting heat from the cooling water through the condenser, this poor combination condenses - COND (11). The liquid is pressurized in the PUMP (7) and passes through the low and high-temperature regenerators, LTR (6) and HTR (5) respectively, before returning to ECON (4), closing the cycle. The main feature of this cycle is the placement of the separator near the turbine to have the high ammonia concentration at the turbine inlet. Several authors have considered this cycle for the generation of energy from low-temperature thermal sources such as geothermal applications (Ogriseck, 2009); (Fu, Zhu, Zhang, & Lu, 2013) e (Zare et al., 2015).

III. KALINA CYCLE INTEGRATION

The Kalina cycle employs a binary working fluid with varying boiling temperatures, which is a combination of ammonia and water. As a result, the temperature profile during boiling and condensation is not consistent, in opposition to the Rankine cycle and ORC. By doing this, we are able to achieve optimal thermal matching between the condenser's cooling medium and waste heat source. Various Kalina cycle layouts have been suggested based on the intended application. With a waste heat stream serving as the heat source, it is made up of a turbine (TUR), generator (GEN), recuperator (RE), condenser (CD), pump (PU), separator (SEP), throttle valve (THV), mixer (MX), and evaporator (EV). This setup is frequently utilized in low-temperature (120–400 C) applications. The ammonia-water mixture in the evaporator is heated to a vapour state using heat recovered from the cooler, preheater, and kiln. After leaving the evaporator, the ammonia-water solution (with an ammonia mass fraction of 83%) enters the separator straight, reaching state 2. The working fluid mixture is split into a weak solution and a vapour with high ammonia content in the separator. The turbine receives direct feed of the ammonia-rich vapour from the separator outlet, with an ammonia mass fraction of 83%. The weak solution travels to the recuperator from the separator in a saturated liquid condition. After expanding through the turbine, the ammonia-rich vapour reaches the mixing point, where it is combined with the working fluid going through the recuperator. After entering the recuperator, the mixed solution exchanges heat with the pump's cold stream. After passing through the condenser and becoming a saturated liquid, the hot stream that exits the recuperator does so. The Kalina cycle condenser is cooled by cooling water that is accessible in the cement plant and has an average temperature of 20^{o}C.

3.1 Kalina Cycle Thermodynamic Analysis

The following assumptions are considered for the analysis of the Kalina cycle: steady-state operation of the cycle, working fluid at the outlet of condenser is saturated liquid, working fluid at the outlet of the turbine is saturated vapour, the temperature of the water source from the cooling tower to the condenser inlet is 20°C, throttling process is isenthalpic, separator completely separates the liquid and vapour, the isentropic efficiency of pump and turbine is 80%, pressure losses and heat losses in pipes are neglected, the effectiveness of the heat exchanger is 80%, all the devices are adiabatic, and the kinetic energy and potential energy changes in the devices are neglected. Mass and energy balance is considered for each cycle component, as follows:

Evaporator: $\dot{m}_1 \cdot (h_2 - h_1) = \dot{m}_{gas} \cdot (h_{out} - h_{in})$

Separator: $\dot{m}_2 \cdot h_2 = \dot{m}_3 \cdot h_3 + \dot{m}_4 \cdot h_4$

Recuperator: $\dot{m}_6 \cdot (h_7 - h_6) = \dot{m}_9 \cdot (h_1 - h_9)$

Turbine: $W_{tur} = \dot{m}_3 \cdot (h_3 - h_5)$

Pump: $\dot{W}_{pul} = \dot{m}_8 \cdot (h_9 - h_8)$

Condenser: $\dot{m}_7 \cdot (h_8 - h_7) = \dot{m}_{cw,cd} \cdot cp_{,cw} \cdot (T_{cw,out} - T_{cw,in})$

Mixer: $\dot{m}_6 \cdot h_6 = \dot{m}_4 \cdot h_4 + \dot{m}_5 \cdot h_5$

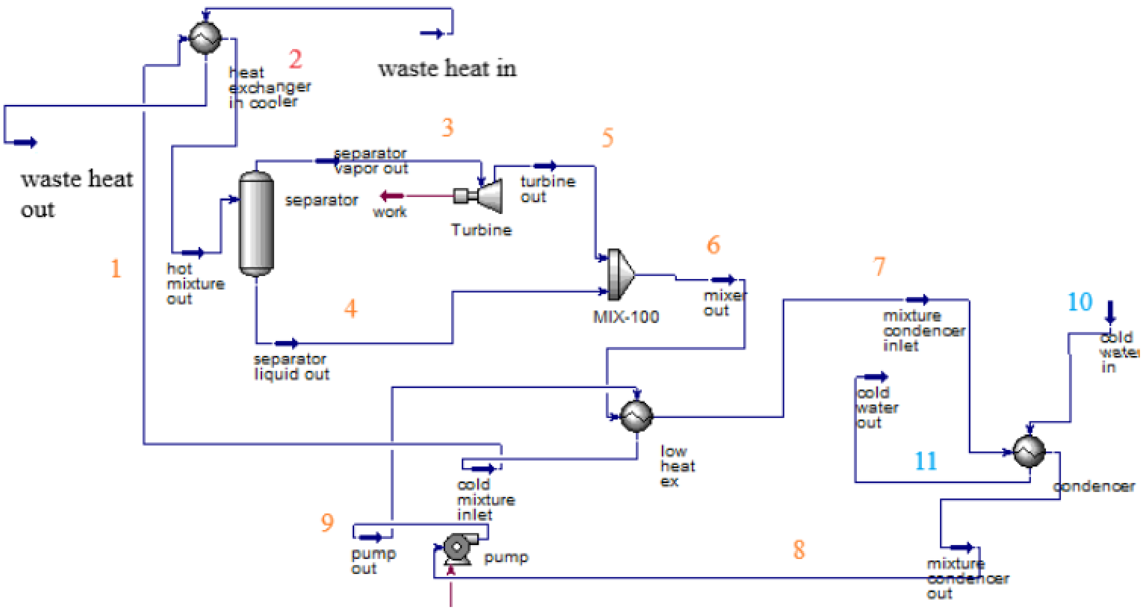

Figure 3: Kalina cycle integration and layout using Aspen software

IV. RESULTS AND DISCUSSION

4.1 kalina cycles driven by separate WHR from cooler, preheater and kiln

Design parameters for the integration of the Kalina cycle for WHR from cooler, preheater, and kiln simulation using Aspen software for each case. We can notice that the values of turbine output power consequently cycle efficiency using WHR from the cooler and preheater are significantly higher than those obtained using the kiln. We can notice from Table -- that the values of turbine output power consequently cycle efficiency using WHR from the cooler and preheater are significantly higher than those obtained using the kiln. And when using combined WHR system we can obtain more power and higher efficiency due to reheating process which effect on fluid inlet turbine temperature after every stage also using only one separator and one pump for all system comparing with using three pumps and separator for separate Kalina single cycle.

Table 1: Design parameters for separate Kalina cycles driven by separate and combined WHR from cooler, preheater, and kiln

Component	Parameter	Separate WHR from cooler	Separate WHR from preheater	Separate WHR from kiln	Combined WHR
WHR (Evaporator)	Shell and tube				
	Temperature of inlet mixture fluid	60 C	60 C	50 C	60 C
	Inlet temperature of hot gas	254 C	314 C	314 C	254 C, 314 C, 314 C cooler, preheater, kiln, respectively
	Outlet temperature of hot gas (Calculated)	96 C	200 C		111 C, 242.4 C, 129.2 C cooler, preheater, kiln, respectively
	Heat exchanger arrangement	Counter-flow	Counter-flow		Counter-flow
	Ammonia mass fraction	83%	83%	83%	83%
	Mass flow rate of fluid mixture	17 kg/s	17 kg/s	8 kg/s	27.7 kg/s
Separator	Drum				
	Minimum separator inlet vapor quality	5%	5%	5%	5%
Recuperator	Drum type				
Turbine					
	Type	Axial Multistage Condensation Back pressure turbine [14]			
	Rated speed	8000 rpm	8000 rpm		
	Isentropic efficiency	90%	90%	90%	90%
	Mechanical efficiency	90%	90%	90%	90%
	Outlet pressure	7 bar	7 bar	7 bar	7 bar
	Inlet pressure	40 bar	40 bar	40 bar	40 bar
	Turbine Inlet Temperature (simulation result)	151.8 C	144.4 C	103.4 C	242.4 C
	Minimum turbine outlet vapor quality	90%	90%	90%	90%
Condenser	Shell and tube type				
	Condenser cooling water inlet temperature	20 C	20 C	20 C	20 C
	Cooling water flow rate	300 kg/s	300 kg/s	144 kg/s	500 kg/s
Pump	Pump efficiency	80%	80%	80%	80%
	Pump power (Calculated)	106 (kW)	106 (kW)	53 (kW)	53 (kW)

Figure 4 presents a series of graphs where the behavior of the net power and the specific electricity generation. It is important to note that the last two variables in this table will not commented on because they do not show a significant influence on the analysed parameters. For a better understanding of the results, it should be understood that during the parametric studies only one parameter varies, whereas the others remain constant with values. In Figure 4-A, it is noted that the increased pressure at the turbine inlet does not represent a significant increase in the net power, but leads to a decrease in the specific electricity generation cost. There is not a substantial increase in the net power with the pressure rise because of the higher operating pressure, although the steam enthalpy increases, causes a decrease in steam generation. This fall leads to a smaller SH and EVAP heat transfer surface area, thus reducing the specific electricity generation cost. Figure 4-B shows that by reducing the steam quality at the evaporator outlet there is an increase in the net power and the specific electricity generation cost. This increase in power is because with a lower steam quality at the outlet of the evaporator, the difference of enthalpies in the evaporation process is lower, allowing more steam to be generated in the evaporator when the temperature difference between states is maintained. The increase in the specific electricity generation cost by reducing the steam quality at the outlet of the evaporator is explained by the fact that, despite the increase in net power and the small reduction of the heat transfer surface area of the evaporator, there is a significant increase in the heat transfer surface area in the super heater. This increase is due to the higher mass flow rate of steam generated for a lower steam quality at the evaporator outlet. Figure 4 (C) shows that increasing the ammonia concentration at the evaporator outlet increases the net power and the specific electricity generation cost. This increase in net power is due to the higher concentration of ammonia at the evaporator outlet; more steam produced in this equipment and in the separator. The increase in the specific electricity generation cost is due to a significant increase in steam production. Which means that the increase in net power does not exceed the increase in cost that causes the rise in the heat transfer surface area in the super heater as the ammonia concentration increased at the outlet of the evaporator? Note that the decrease of the heat transfer surface area in the evaporator is relevant with the increase of the ammonia concentration at the outlet of the evaporator, but is smaller than the growth of the heat transfer surface area in the super heater. In Figure 4 (D) it is observed that by increasing the temperature difference in the EVAP, between the states '19' and '9', there is a significant reduction in the net power, with a specific electricity generation cost approximately constant. A more considerable temperature difference in EVAP necessarily implies a lower steam generation in the evaporator, resulting in a lower mass flow, which has a direct impact on the net power. The small variation of the specific electricity generation cost and the reduction of costs are related to the smaller heat transfer surface area in the super heater and the evaporator.

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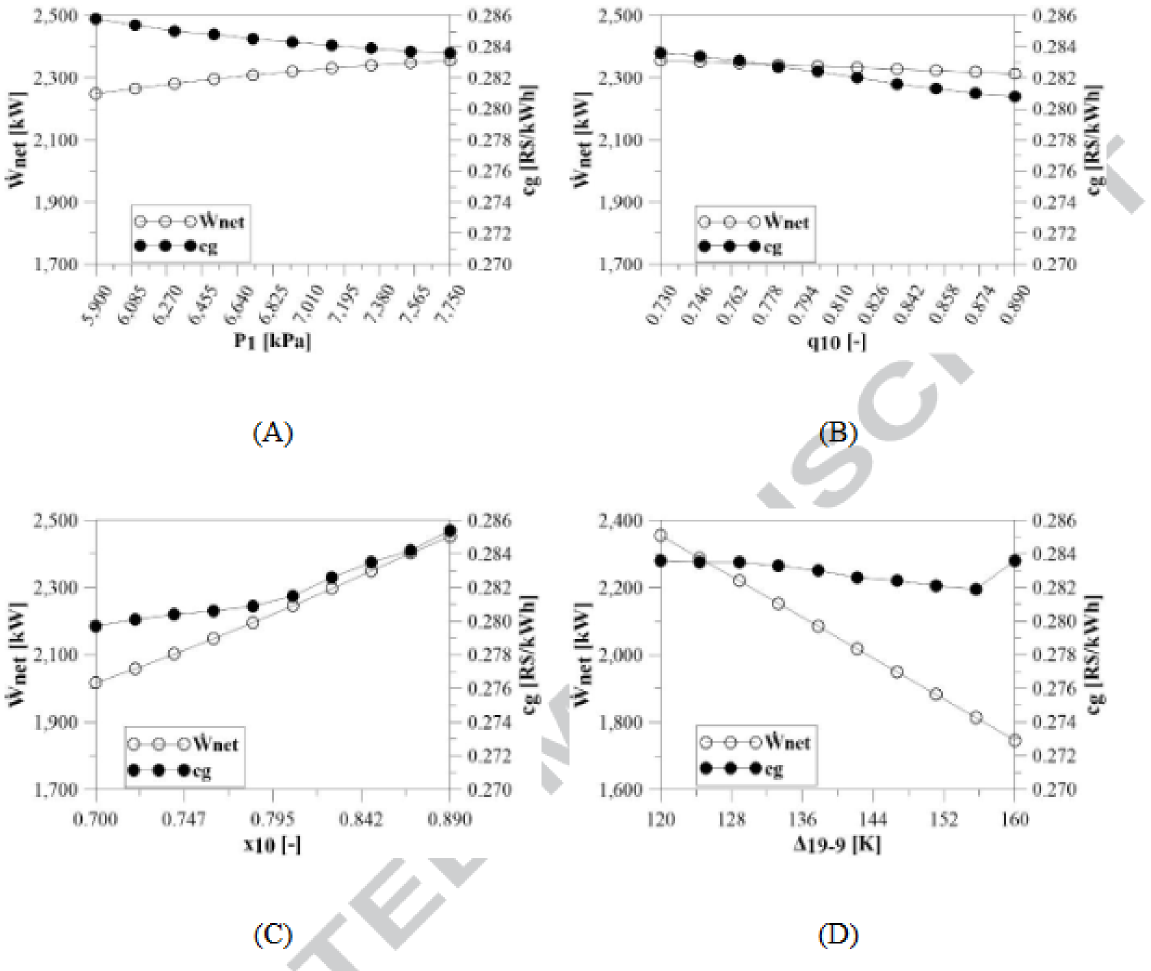

Figure 4: Influence of variables on the optimization parameters

V. CONCLUSIONS

Detailed waste heat analysis and recovery from a typical cement plant using the Kalina cycle have been carried out using ASPEN software. The annual heat losses from the kiln surface, preheater, and the cooler are estimated as 79.23, 44.32, and 43.6 GWh at average temperatures of about 314, 314, and 254^{o}C, respectively. The present analysis indicates WHR for power generation with a maximum efficiency of 44 to 50% can be integrated with the cement plant. Two design alternatives for Kalina cycle integration in the cement plant using separate and combined WHR from the kiln surface, cooler, and preheater have been investigated. The design parameters for each configuration have been determined following a parametric study for the effect of turbine inlet pressure, mass flow rate, and ammonia water concentration. The efficiency of the Kalina cycle increases with increasing ammonia concentration at the evaporator outlet and increasing turbine inlet pressure. The results show that, for separate WHR, turbine output electric power from cooler, preheater, and kiln shell are 3.31 MW, 3.06 MW and 3.02 MW respectively with a total net output power of approximately 9.165 MW. The values of the cycle efficiency are 32.4%, 28.55 %, and 23.2% for WHR from cooler, preheater, and kiln, respectively. The low efficiency of WHR from the kiln is attributed to the use of secondary shell with limitations on surface heat transfer due to mechanical parts rotation and maintenance requirements as well as low convection heat transfer. The value of net power output using combined WHR is about 9.35 MW as compared to 8.86 using a separate WHR design. A cost-saving of about 23% with about 7% increasing of the total produced electricity power has been obtained using Kalina cycle in combined WHR as compared to separate WHR design.

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