

Energetic and Exergetic Evaluation of 4 Systems for a Rotary Kiln Improvement

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The energy balance of a rotary kiln used for calcination of 4400 kg/h of dolomite in a magnesium production company identified the kiln shell (26.35% of the input energy) and exhaust gases (18.95%) as the major sources of heat losses. To increase the efficiency of the kiln, the following systems are analyzed by the use of energy and exergy analysis: (i) system for preheating of the combustion air by heat exchange with the exhaust gas; (ii) system for space and DHW heating in the company by water heating with the exhaust gas sensible heat; (iii) system that consists of a recuperator that use sheat loss from the kiln shell to preheat the combustion air (designatedas iii-a) and the system given in (ii); and (iv) system that consists of (iii-a) and an cogeneration system that uses organic Rankine cycles upplied with heat by heat exchange with the exhaust gas. The system (ii) is the optimal solution by economic criteria because the company uses relatively expensive heavy fuel oil for space heating, where as exergetically, the most efficientis the the system (iv), which enables the kiln to have the exergetic efficiency of 36.02%.

Keywords: electrical cabinets, heat transfer, natural convection, forced convection, wall construction.

1. INTRODUCTION

This paper considers four systems for heat recovery. In each of the cases of the waste heat is used for the products of combustion rotary kiln. The waste heat is meant the losses contained in the natural heat of the combustion products and those who surrender to the surroundings through the mantle rotary kiln. Were considered forth the following systems for the utilization of waste heat rotary kiln:

- System for heating the combustion air, the heat contained in the flue gases (i).
- System for heating water (the water in the winter used to heat the hall, and in the summer for domestic hot water) heat contained in the flue gases (ii).
- The system for heating the water by heat contained in the exhaust gas in combination with a heat exchanger which uses the waste heat from the rotary kiln sheath (iii).
- System for the use of heat in the flue gases to produce electricity by Rankin - Klauzijus circular process with an organic working fluid in combination with a heat exchanger that uses waste heat from the mantle rotary kiln (iv).

RC process is historically the longest used to produce electricity. Today is to increase the degree of usefulness RC process when using a lower temperature heat source is often used instead of water vapour, organic working fluids in the ORC. Until the election of this process there is also the basis of the recommendations that can be found in the relevant literature. To approximately 1 MW of heat contained in the products from the rotary kiln on the basis of the diagram given in Figure 1 is the most optimal for the production of electrical energy using ORC.

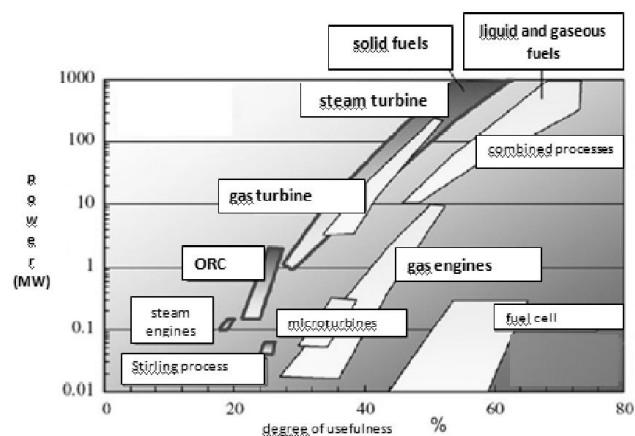


Figure 1: Degrees of usefulness and power ranges that use different systems for the production of electrical energy. ORC - Organic Rankine Cycle. (diagram originates from (Karl, 2004), and retrieved from (Karellas, et al, 2008))

2. POSSIBILITY USE OF WASTE HEAT FROM THE ROTARY KILN

Based on the previously approved system for the use of waste heat rotary kiln below to be shown the material and heat balances of each system.

2.1. System for heating the combustion air, the heat contained in the flue gases

The heat contained in the exhaust gas is used to heat air that is then used to fuel combustion in rotary kiln. Products of combustion at the entrance to the heat exchanger have a temperature of 343°C. In the heat exchanger products are cooled to a temperature of 150°C, wherein the combustion air is heated from 20°C to 312°C.

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Material and heat balance of the system is given in Table 1.

In order not to jeopardize the operation of the filter, the products must be neither too high nor too low temperature (condensation). To solve the problem of high temperatures in the existing structure products to mix with the surrounding air so that the temperature of the products is not higher than 130°C. A schematic representation of this system is shown in Figure 2. In Table 2, the calculation of fuel savings that can be achieved by using this solution.

Table 1: Material and heat balance system for heating degree air

| | | |
|--|---------|---------|
| The available heat which can be used for heating the air | 1006,27 | kJ/s |
| Mass flow rate of combustion air | 3,379 | kg/s |
| Inlet air temperature | 20 | °C |
| Assumed output air temperature | 312,08 | °C |
| Mean temperature of the heated air | 166,04 | °C |
| Specific heat capacity of air (for high temperature) | 1,0197 | kJ/kg K |

Table 2: Calculation of fuel savings

| Input energy | | kJ/kgcal | % |
|-----------------------------|---|----------|----------|
| | Combustion of fuels (Q ₁) - LHV | 7435,44 | 98,96 |
| | Natural heat of fuel (Q ₂) | 41,07 | 0,55 |
| | Natural heat of air (Q ₃) | 22,25 | 0,30 |
| | Natural heat of the raw material (dolomite) (Q ₄) | 14,82 | 0,20 |
| | Total: | 7513,58 | 100,00 |
| The input data | | | |
| | Mass flow rate of fuel | 0,184 | kg/kgcal |
| | Lower heating value of fuel - LHV | 40410 | kJ/kg |
| | Specific heat capacity of the fuel | 1,717 | kJ/kg |
| | The fuel temperature | 130 | C |
| | Specific heat capacity of air | 1,006 | kJ/kgK |
| | Specific heat capacity of the raw material (dolomite) | 0,92 | kJ/kgK |
| | Production calcine | 4399 | kgcal/h |
| Calculation of fuel savings | Temperature of combustion air | 312,08 | °C |
| | Specific heat capacity of the heated air | 1,01967 | kJ/kgK |
| | Natural heat of air (Q ₃) | 879,89 | kJ/kgcal |
| | The fuel consumption, the use of heated air | 0,1629 | kg/kgcal |
| | The difference in fuel consumption (savings) | 0,0211 | kg/kgcal |
| | The percentage of fuel savings | 11,47 | % |
| | The amount of fuel saved | 2228,36 | kg/ day |

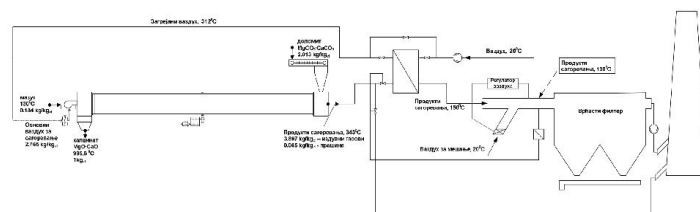


Figure 2: System for heating vazduka using the waste heat of the combustion products

2.2. The system for heating the water by heat contained in the exhaust gas

System for water heating is designed so that the water in the winter used to heat the hall, and in the summer for domestic hot water in a large central tank. Operating pressure in the system is 6 bars. The water is heated in the exchanger where the combustion products are cooled to 343°C to 150°C where in the water is heated from 50°C to 149,3°C. Material and heat balance of the system is shown in Table 3.

Table 3: Material and heat balance system for heating water

| | | |
|--|---------|---------|
| The available heat which can be used to heat the water | 1006,27 | kJ/s |
| The mass flow of water | 2,40 | kg/s |
| Water inlet temperature | 50 | °C |
| Assumed water outlet temperature | 149,3 | °C |
| Medium temperature water | 99,65 | °C |
| Specific heat capacity of water (for high temperature) | 4,22 | kJ/kg K |

The system for heating the water is shown in Figure 3 wherein they are shown in the same figure, and the other components of the system. As has already been said bag filter must be provided as in the previous case.

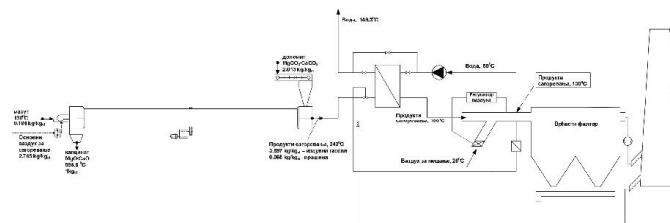


Figure 3: The system for heating the water by heat contained in the exhaust gas

2.3. The system for heating the water by heat contained in the exhaust gas in combination with a system for recovery of heat from the rotary kiln sheath.

This system relies on the previous with the existing components of the system adds heat exchanger where it heats the combustion air. Model exchanger with material and heat balance is given in the paper entitled „Recuperator for waste heat recovery from rotary kilns“, Vladan Karamarković, Miljan Marašević, Rade Karamarković, Miodrag Karamarković, Applied Thermal

Engineering, Volume 54, Issue 2, 30 May 2013, Pages 470–480, DOI: 10.1016/j.applthermaleng.2013.02.027. Material and heat balance exchanger which heats water is the same as in the previous section. With this system, water is heated in the exchanger from 50°C to 149,3°C whereby the recuperator heats the combustion air to a temperature of 299,6°C. In Table 4, the calculation of fuel savings that can be achieved by using this solution. Figure 4 is a schematic showing alternative solution with components.

Table 4: Fuel savings using the heat exchanger

| | | |
|---|---------|----------|
| The total energy input | 7513,58 | kJ/kgcal |
| The temperature of the heated air | 299,60 | C |
| Specific heat capacity of the heated air | 1,0454 | kJ/kgK |
| The heat of the hot air | 866,00 | kJ/kgcal |
| Fuel consumption by using heat exchangers | 0,1632 | kg/kgcal |
| The amount of fuel saved per pound of product | 0,0208 | kg/kgcal |

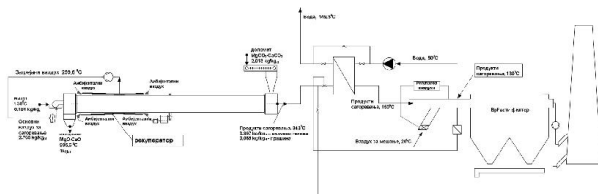


Figure 4: System for heating air and water using waste heat rotary kiln

2.4. System for the use of heat in the flue gases to produce electricity

With this system it is important to note that the analysis is carried out when the electricity generation using ORC cycle in combination with energy recovery that uses waste heat from the mantle rotary kiln (as in the previous case). Below is given a brief introduction of ORC systems with a choice of working medium.

2.4.1. ORC cycle theoretical basis

ORC is a thermodynamic process, which takes its name from the fact that it uses an organic fluid, high molecular weight, in which the phase change liquid-vapor takes place at lower temperatures than the saturation phase changes in water vapor in the case of Rankine's process.

Such cycles available thermal energy is converted into useful mechanical work, and continue this work can be converted into electricity. The first prototype was developed and introduced in 1961., Israeli engineers for solar energy Harry Zvi Tabor and Lucien Bronicki [16].

The principle of operation of ORC is similar to that of Rankine's process: the working fluid increases the pressure in the pump to the working pressure increased by the pressure drop in the heat exchangers and pipelines. The working fluid in the heat heat is applied, wherein the working fluid further heated by the supply of heat and evaporates. Then, the working fluid is expanded in a

turbine and then is condensed in condenser. So chilled working fluid is returning to the beginning of the process, i.e. the pump.

2.4.2. ORC cycle for electricity production

This paper analyzes the possibilities of ORC processes as working medium using isopentane. Isopentane was selected on the basis of practical examples where in similar product temperature at the exit of the rotary kiln cement recommended this working fluid. Operating pressures of the process are 30 bar and 1.4 bar. The mass flow of the working fluid (isopentane) is 1.5 kg / s. The adopted parameters of the system are presented in Table 5 and the values of the thermodynamic properties characteristic points given in Figure 5.

Table 5: Parameters ORC system

| | |
|--|----|
| Degree of goodness expansion turbine (%) | 85 |
| Mechanical efficiency level of the turbine (%) | 99 |
| Efficiency pumps (%) | 98 |
| Mechanical efficiency level generator (%) | 98 |
| Electrical efficiency level generator (%) | 98 |

ORC-tacke.rfp - REFPROP (isopentane) - NIST Reference Fluid Properties -

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| | Temperature (K) | Pressure (MPa) | Density (kg/m ³) | Enthalpy (kJ/kg) | Entropy (kJ/kg-K) |
|---|-----------------|----------------|------------------------------|------------------|-------------------|
| 1 | 310.67 | 0.14000 | 602.01 | 22.473 | 0.073277 |
| 2 | 311.76 | 3.0000 | 605.43 | 27.210 | 0.073277 |
| 3 | 452.65 | 3.0000 | 352.51 | 438.81 | 1.1439 |
| 4 | 452.65 | 3.0000 | 126.21 | 545.31 | 1.3792 |
| 5 | 495.38 | 3.0000 | 73.720 | 698.07 | 1.7032 |
| 6 | 420.54 | 0.14000 | 2.9459 | 577.37 | 1.7544 |
| 7 | 310.67 | 0.14000 | 4.1392 | 358.11 | 1.1536 |
| 8 | 310.67 | 0.14000 | 602.01 | 22.473 | 0.073277 |

Figure 5: Values characteristic points ORC process

With this system, the generator may get 172,18 kW of electric power, wherein in the condenser water is heated from 20°C to 103°C. In addition to the recuperator is heated combustion air to a temperature of 299,6°C. Figure 6 schematically shows alternative solution with components.

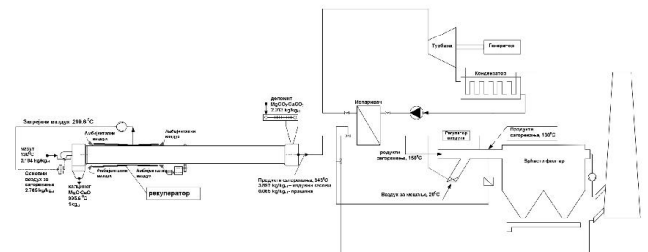


Figure 6: System for the use of heat in the flue gases through the ORC process

3. EXERGY ANALYSIS

On the basis of calculations in the previous section for each of the systems further in this paper was carried out Exergy calculation of selected solutions.

3.1.1. Technical Working power or exergy

The second law of thermodynamics indicates irreversible processes as the primary causes of energy loss. Their consequence is an increase in entropy ΔS which leads to energy losses. Loss of work and the amount of heat [2]:

$$\Delta L = T_0 \Delta S \quad (3.1)$$

$$\Delta Q = T_0 \Delta S T / (T - T_0), \quad (3.2)$$

Although previous formulas allow to calculate the loss of work (3.1) and the amount of heat (3.2), they do not provide a measure of the energy loss of the total energy that is participating in a process. This measure provides technical working power (Bošnjaković, 1978). For a substance that steady stream, it is a work that would theoretically could get if these substances on the reversible manner, brought into balance with its surroundings and pushed out into the environment. For technical working power Zoran Rant proposed name of Exergy (Bošnjaković, 1978). For that matter, current technical working power or exergy is:

$$E = H - H_0 - T_0 (S - S_0), \quad (3.3)$$

where:

H and S refer to the state of matter which is not in equilibrium with the environment

H_0 and S_0 - the state of matter in equilibrium with the environment (p_0, T_0)

Exergy E_Q some amount of heat Q, which is subtracted the heat source temperature T is:

$$E_Q = Q (T - T_0) / T. \quad (3.5)$$

From equation (3.5) we see that the heat can be converted into work at temperatures higher than the ambient temperature T_0 . Heat to the ambient temperature of the Exergy worthless because there is the potential to turn into a paper [2].

3.1.2. Exergy analysis of systems using waste heat rotary kiln

Exergy is the maximum work that can be produced by a system, the flow of fluid or energy in its bringing into balance with the reference environment [7] (taken from [8]). This thermodynamic condition takes into account the increase in entropy due to irreversibility, i.e. the second law of thermodynamics, and is a suitable tool for analyzing the process of energy transformation. Exergy balance of the test furnace, or of any other process of energy transformation can be represented in the following form, taking into account all energy flows entering and leaving the system:

$$\sum_{in} Ex_i = \sum_{out} Ex_k + I \quad (3.6)$$

where:

$\sum_{in} Ex_i$ - the sum of all exergy input current.

$\sum_{out} Ex_k$ - the sum of all exergy output current.

The difference between the sum of all input and output flows exergijskih called irreversibility I. Irreversibility is the internal loss of exergy in the process of [9]. This loss is due to an increase in entropy caused by the irreversibility that occur due to: chemical reactions, heat and mass transfer and fluid flow [9].

Exergy amount of heat that the mantle rotary kiln is lost to the surroundings is:

$$Ex_Q = \sum_{i=1}^{24} Ex_{Q_{s,i}} = \sum_{i=1}^{24} \left(1 - \frac{T_0}{T_{s,i}} \right) \frac{Q_{s,i}}{m_{s,i}}, \quad (3.7)$$

Analyzed a rotary kiln with appropriate exchangers has several inputs (fuel, air, dolomite, water) and output (calciner, combustion products, dust, water, electricity) material flows. For each of them, the exergy Ex_i , is dependent on the composition (chemical exergy $Ex_{ch,i}$), and the temperature and pressure (the physical exergy $Ex_{ph,i}$):

$$Ex_i = Ex_{ch,i} + Ex_{ph,i} = m_i (e_{ch,i} + e_{ph,i}) \quad (3.8)$$

The physical exergy of a compound and is:

$$e_{ph,i} = (h - h_0)_i - T_0 (s - s_0)_i \quad (3.9)$$

where:

h and s - the enthalpy and entropy of a given flow at a temperature and pressure

h_0 and s_0 - the enthalpy and entropy of a given flow at ambient temperature and pressure

Physical exergy of the combustion products is equal to the sum of the physical exergy of gaseous components contained in the exhaust gas.

Standard chemical exergy of a pure chemical compound (which is not a mixture) e_{ch}^0 is equal to the maximum work obtained when this compound with pressure (p_0) and temperature (T_0) environment lead to the so-called. Dead state, determined that the same pressure (p_0) and temperature (T_0) temperature and concentration of the reference substance in a standard atmosphere

Standard reference condition defined by the temperature 298.15K and pressure of 101,325 kPa. Table 6 shows the standard chemical exergy of all the components shown in the material balance.

Table 6: Standard chemical exergy e_{ch}^0 [10], [11].

| Gas | Standard chemical exergy e_{ch}^0 (kJ/mol) | Solids | Standard chemical exergy e_{ch}^0 (kJ/mol) |
|------------------|--|--|--|
| CO ₂ | 19.48 | Dolomite CaCO ₃ ·MgCO ₃ | 32.2 |
| SO ₂ | 313.4 | | |
| H ₂ O | 9.5 | CaO | 127.3 |
| N ₂ | 0.72 | | |
| O ₂ | 3.97 | MgO | 59.1 |

The chemical exergy of the mixture, such as products of combustion, is dependent on the composition of the mixture and is defined by the formula:

$$e_{\text{mixture}} = \sum_i y_i e_{\text{mix},i}^0 + RT_0 \sum_i y_i \ln y_i \quad (3.10)$$

Chemical exergy of the mixture is always lower than the sum of the individual components of exergy. The second member of the above equation is the so-called. Exergy of mixing and is always negative [9].

Chemical Exergy calciner depends on the mass fraction of CaO and MgO in it:

$$e_{\text{CaO}}^0 = \sum_i x_i \left(\frac{e_{\text{CaO}}^0}{M_i} \right) = x_{\text{CaO}} \left(\frac{e_{\text{CaO}}^0}{M_{\text{CaO}}} \right) + x_{\text{MgO}} \left(\frac{e_{\text{MgO}}^0}{M_{\text{MgO}}} \right) \quad (3.10)$$

Exergy efficiency level is the ratio of exergy that comes out of the system and the exergy entering the system [21]:

$$\psi = \frac{\sum_{\text{out}} Ex_i}{\sum_{\text{in}} Ex_j} \quad (3.11)$$

Degree Exergy efficiency is defined as the ratio of useful exergy obtained and entered total exergy:

$$\psi_k = \frac{Ex_{\text{product}}}{\sum_{\text{in}} Ex_j} \quad (3.12)$$

3.1.3. Exergy efficiency of the proposed solutions for the use of waste heat rotary kiln

In this part of the paper presents the exergy calculations of the proposed solutions and the values of exergy input and output streams [3].

Exergy analysis results performed for the case of heating of combustion air, the heat contained in the exhaust gas (Figure 2) are presented in Table 7.

Table 7: Exergy calculation of using the waste heat of the combustion products for heating the air

| | | | | |
|-----------------------------------|-----|---|----------|----------|
| Output flows | I.1 | Exergy combustion products | 797,117 | kJ/kgcal |
| | I.2 | Exergy loss of heat from the mantle rotary kiln | 815,25 | kJ/kgcal |
| | I.3 | Exergy calcine | 2426,21 | kJ/kgcal |
| | I.4 | Exergy dust | 25,26 | kJ/kgcal |
| Input flows | U.1 | Exergy dolomite | 352,424 | kJ/kgcal |
| | U.2 | Exergy of air | 1,404 | kJ/kgcal |
| | U.3 | Exergy fuel | 7917,481 | kJ/kgcal |
| Useful exergy efficiency ψ_k | | | 29,33 | % |

Exergy analysis results performed for the case of hot water (water in the winter used to heat the hall, and in the summer for domestic hot water) heat contained in the flue gases. (Figure 3) are presented in Table 8. In this case, a useful exergy efficiency is defined:

$$\psi_k = \frac{\text{useful exergy}}{\text{total input exergy}} = \frac{E_{\text{x calcine}} + E_{\text{x water}}}{\sum_{\text{in}} E_{\text{xj}}} \quad (3.13)$$

Table 8: Exergy calculation of using the waste heat of the combustion products for heating water

| | | | | |
|-----------------------------------|-----|---|----------|----------|
| Output flows | I.1 | Exergy combustion products | 797,117 | kJ/kgcal |
| | I.2 | Exergy loss of heat from the mantle rotary kiln | 815,25 | kJ/kgcal |
| | I.3 | Exergy calcine | 2426,21 | kJ/kgcal |
| | I.4 | Exergy dust | 25,26 | kJ/kgcal |
| | I.5 | Exergy heated water | 172,899 | kJ/kgcal |
| Input flows | U.1 | Exergy dolomite | 352,424 | kJ/kgcal |
| | U.2 | Exergy of air | 1,404 | kJ/kgcal |
| | U.3 | Exergy fuel | 7917,481 | kJ/kgcal |
| | U.4 | Exergy water | 8,145 | kJ/kgcal |
| Useful exergy efficiency ψ_k | | | 31,39 | % |

Table 9 shows the results ekssergijskog calculations for the case when the water is heated by the waste heat of the combustion products in combination with energy recovery that uses waste heat to pay rotary kiln (Figure 4).

Table 9: Exergy calculation of using the waste heat of the combustion products for heating water in combination with energy recovery

| | | | | |
|-----------------------------------|-----|---|----------|----------|
| Output flows | I.1 | Exergy combustion products | 705,047 | kJ/kgcal |
| | I.2 | Exergy loss of heat from the mantle rotary kiln | 404,75 | kJ/kgcal |
| | I.3 | Exergy calcine | 2426,21 | kJ/kgcal |
| | I.4 | Exergy dust | 25,26 | kJ/kgcal |
| | I.5 | Exergy heated water | 172,899 | kJ/kgcal |
| Input flows | U.1 | Exergy dolomite | 352,424 | kJ/kgcal |
| | U.2 | Exergy of air | 1,404 | kJ/kgcal |
| | U.3 | Exergy fuel | 6967,224 | kJ/kgcal |
| | U.4 | Exergy water | 8,145 | kJ/kgcal |
| Useful exergy efficiency ψ_k | | | 35,46 | % |

In systems for the use of heat in the flue gases to produce electricity by Rankin-Klauzjusovog circular process with an organic working fluid (Figure 5) results ekssergijskog calculations are shown in Table 10 should be noted that in this case the useful exergy efficiency is determined:

$$\psi_k = \frac{E_{\text{x calcine}} + E_{\text{x electricit y}} + E_{\text{x water}}}{\sum_{\text{in}} E_{\text{xj}}} \quad (3.14)$$

Table 10: Exergy calculation system for waste heat recovery products of combustion to produce electricity ORC cycle in combination with energy recovery

| | | | | |
|--------------|-----|---|---------|----------|
| Output flows | I.1 | Exergy combustion products | 705,047 | kJ/kgcal |
| | I.2 | Exergy loss of heat from the mantle rotary kiln | 404,75 | kJ/kgcal |
| | I.3 | Exergy calcine | 2426,21 | kJ/kgcal |
| | I.4 | Exergy dust | 25,26 | kJ/kgcal |
| | I.5 | Exergy heated water | 72,244 | kJ/kgcal |

| | | | | |
|--------------------------------------|-----|--|----------|----------|
| | I.6 | Exergy derived electricity | 140,907 | kJ/kgcal |
| Input flows | U.1 | Exergy dolomite | 352,424 | kJ/kgcal |
| | U.2 | Exergy of air | 1,404 | kJ/kgcal |
| | U.3 | Exergy fuel | 6967,224 | kJ/kgcal |
| | U.4 | Exergy water | 0,349 | kJ/kgcal |
| | U.5 | Exergy of electricity needed to operate the pump | 5,933 | kJ/kgcal |
| Useful exergy efficiency η_{FE} | | | 36,02 | % |

4. COMPARATIVE ANALYSIS SYSTEM OF THE USE OF WASTE HEAT COMBUSTION PRODUCTS

Based on the conducted energy and exergy analysis can be carried out comparison of the proposed solutions. Values useful exergy efficiency degree of usefulness and analyzed solutions are presented in Table 11.

Table 11: Useful exergy efficiency for the proposed system

| | The proposed alternative solution for the use of waste heat | Useful exergy efficiency (%) |
|-------|---|------------------------------|
| (i) | System with heated air | 29,33 |
| (ii) | System to heat water without the use of a recuperator | 31,39 |
| (iii) | System for heating water using a recuperator | 35,46 |
| (iv) | System for the production of electricity ORC process with recuperator | 36,02 |

The analysis of the results shown in the table above it can be seen, as expected, that the use of heat from the mantle furnace and waste heat from flue gases more efficiently than using only waste heat from flue gases. Of all the systems the most efficient system in which the waste heat is used in the cogeneration process for the production of electricity. The reason lies in the fact that this process of most exergy of flue gases usefully spent. In the process of cogeneration least the irreversibility because the minimum temperature difference in the exchanger where the flue gas takes heat. Environmentally speaking, the process of cogeneration is the best because it reduces the emissions of pollutants from the power system of the Republic of Serbia. In fact, almost 70% of electricity in our country is produced in power plants. The system (ii) is the optimal solution by economic criteria because the company uses relatively expensive heavy fuel oil for space heating, where as exergetically, the most efficient is the system (iv), which enables the kiln to have the exergetic efficiency of 36.02%.

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