Designing Recuperator on a Rotary Kiln Supplied with Enriched Air During the Calcination of Dolomite

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The paper analyzes the possibility of using a recuperator on a rotary kiln in the case where the heat for calcination of dolomite is obtained by the combustion of heavy fuel oil (HFO) with enriched air. The combustion air is enriched with oxygen up to 23%. The recuperator uses both the convective and radiant heat loss from the mantle, prevents overheating and could be implemented over rotary kilns with similar surface temperature distribution. A mathematical model that determines the diameter of the recuperator is developed and presented. The use of the suggested recuperator is impossible when air enriched with oxygen over 23% is used for the combustion of HFO in the kiln. It is necessary to consider other possibilities for the use of waste heat from the mantle of a rotary kiln.

Keywords: rotary kiln, waste heat, recuperator, enriched air.

1. INTRODUCTION

The increased efficiency in non-ferrous metallurgy has a very great potential in the process of dolomite calcination, which is carried out in rotary kilns. The thermal efficiency of energy transformation is relatively low in the process of dolomite calcination in rotary kilns, and range between 55% and 60% (usable heat means the heat of decarbonisation and physical heat of produced calciner) [1].

The most prominent heat losses are:

- Loss due to external cooling through the mental of a rotary kiln (up to 30% of the energy input),
- Loss contained in the physical heat of combustion products (20% of the energy input).

In addition to these losses, the problems of more efficient operation of rotary kilns represent and the lower actual combustion temperature in the calcination zone. Lower actual temperatures have a negative effect on the quality of produced calciner and in further production, lead to increased specific energy consumption in electrical kilns.

Enrichment of combustion air is one of the ways to increase the efficiency of rotary kilns and before all, their capacity. The enrichment procedure results in a reduced amount of nitrogen, decreased volume and reduced loss of physical heat in exhaust gases. On the other hand, enrichment of air with oxygen causes an increase in the burning rate, temperature, composition and aerodynamic properties of the flame. Higher temperatures of fuel combustion cause the improvemed of calciner quality and intensify heat radiation in the calcination zone.

However, there are negative effects that accompany the use of enriched air. With the increase in combustion temperatures, the heat loss due to external cooling increases, too. The increased temperature in the calcination zone results in a higher temperature at the mental of the rotary kiln, which increases heat loss.

2. OXYGEN IN THE COMBUSTION PROCESS

The well-known properties of oxygen are that it is colourless, odorless; in liquid stage, oxygen has a distinctive light blue color and it is slighty heavier then water. Comperd with air combustion, combustion with enriched air is more intense and followed by higher combustion temperatures.

Table 1.1 Physical properties of oxygen [1]

Dimensions	Tags	Value	Unit
Molecular mass	M	32	kg/k mol
Gas constant	R	259.9	J/kg K
Density (at 0^0 C and 1 bar)	ρ_o	1.429	kg/m^3
Boiling temperature (at 1 bar)	t_s	-182.98	$^\circ$C
Liquid density (at the boiling temperature)	ρ	1140	kg/m^3
Specific heat capacity (at 0^0 C and 1 bar)	c_p	913	J/kg K
Specific heat capacity (at 0^0 C and 1 bar)	c_v	653	J/kg K
Adiabatic exponent	κ	1.4	-
The heat of vaporization (1bar)	r	213	kJ/kg
Critical temperature	t_k	-118.82	$^\circ$C
Critical pressure	p_k	50.37	bar
Thermal conductivity (at 0^0 C and 1 bar)	l	0.024	W/m K

2.1. Methods of enriching the air with oxygen

The use of oxygen has led to the fact that two different basic methods of enriching the air with oxygen are:

-equivalent enrichment,
-additional enrichment.

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In equivalent air enrichment, the amount of air is reduced while a certain amount of oxygen is added and the total amount of oxygen for combustion is not changed.

In additional air enrichment, the amount of air is not changed, but desired amount of oxygen is added to the air.

2.2. Extraction methods of oxygen

There are several methods for extraction of oxygen from air [2]:

-cryogenic distillation,
-molecular sieves and
-absorption process.

The selection of method for separation of air into its components is applied depends on various factors, including the requirements of the technological process, economic, i.e. financial conditions and security of the entire systems. Atmospheric air is separated into its main components: nitrogen and oxygen, while argon and some other inert gas are sometimes extracted. The adsorption process in the literature, is called Pressure Swing Adsorption (PSA), or adsorption process with alternating change of the pressure (adsorption and desorption).

2.3. Methods for oxygen introduction

There are three methods for introducing oxygen in a rotary kiln:

-Direct, in air canal,
-Direct, using nozzles and
-Using a special burner,

The direct method is the oldest and most famous method for oxygen introduction. The low investment cost and simplicity are the main advantages of this method. The positive sides of this method are obvious even for the small quantities of enrichment (1-2% of oxygen). The direct method of introduction of oxygen into the canal is used in this paper.

3. ROTARY KILN

At the magnesium production company “Bela Stena” in Baljevac on the river Ibar, the “magnetherm” process is used for the production of magnesium. Figure 3.1 shows the main parts of the line for production of dolomite calciner [2]:

- Supply system,
- Driving unit,
- Receiving storage for calcined material,
- Cooler for gases,
- A bag filter for purification of exhaust gases,
- Dust transportation system,
- Fan,
- Chimney.

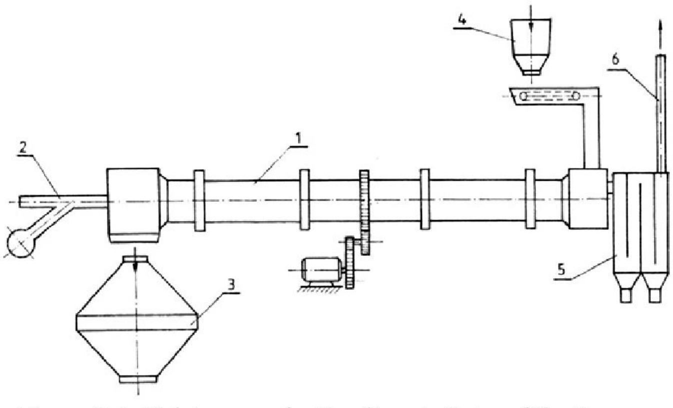

Figure 3.1. Calciner production line. 1. Rotary kiln. 2. Burner. 3. Calciner storage. 4. Dolomite storage. 5. Electrostatic precipitator. 6. Chimney.

Table 3.1 Characteristics of the rotary kiln

Manufacture	FIVES CAIL - BABCOCK - FRANCUSKA
External diameter of kiln	2800 mm
Length of kiln	80m
Kiln inclination	3 %
Rotation per minute (Rpm)	0.75 - 0.95 min^{-1}
Nominal capacity	135t of calciner per day
Kiln capacity	9150 kg/h
Fuel	Heavy oil

Raw dolomite is double carbonate ($CaMg(CO_3)_2$) with a slight admixture of manganese and iron. The transportation system transports raw dolomite from reception bunker to the crusher. After crushing, dolomite goes to washing where mechanical impurities are removed. The purified dolomite passes through the sieves, resulting in a dolomite grain size of 3 to 30mm. The belt conveyer transports grained dolomite to the bunker located above the rotary kiln. The mechanical feeders continuously feed the rotary kiln with dolomite. Due to the rotation and inclination of the kiln, dolomite is slightly moves with stirring through kiln, lifts up by the rotation wall a the certain height and then drops through the stream of hot gases. Dolomite passes several temperature zones on its way through the rotary kiln.

The mantle of a rotary kiln can be divided into few temperature zones or areas.

At about 20m of kiln length, temperature values are in the range between 100 and 400°C and that part of the kiln is made of refractory concrete (3m of length) and the second part is coated with refractory bricks (17m of length) and this is the preparation zone. In this zone of the rotary kiln, fins or buckets are used to lift up dolomite.

At the next 40m, the temperature value is around 700°C and for this part of the rotary kiln improved materials are used for the kiln wall. This is the drying zone.

At the last 20m, the temperature is around 1300°C, and the quality of refractory bricks is best in this part of the kiln. This is the calcination zone. In this zone, calcination of dolomite takes place according to the chemical reaction:

$$CaCO_3 \cdot MgCO_3 \rightarrow CaO \cdot MgO + 2CO_2 \qquad (3.1)$$

4. RECUPERATOR

In order to increase energy efficiency of the current production line, it is very important to reduce heat loss from the mantle of the rotary kiln. In cement industry, this loss is 8-15% of the total heat input [2], while in the magnesium production process it is higher. Chakrabarti [3] obtained even larger losses, 24.8% of the total heat input for the rotary kiln located in the hall and 34.7% of the total heat input for the rotary kiln located in the open air.

Among the factors that affect this heat loss are: technological characteristics of inside process of the kiln, temperature distribution, thermal stability and resistance of refractory lining inside the kiln, ambient conditions at the kiln location, kiln dimensions, thermal properties of the outer insulating layer and rotational speed.

The heat loss of the rotary kiln to the surroundings is either reduced by the use of the heat exchangers or by the use of stationary insulation screens around the kiln [7, 8]. The heat exchangers are also a part of external shell [4, 5], and they are usually used to preheat the water for district heating systems.

As mentioned in the previous sections, an examination rotary kiln is used for calcination of dolomite in the magnesium production company. The requirement to utilize the total heat loss by radiation and convection was the reason to utilize waste heat to preheat the air used for the combustion of fuel.

Figure 4.1 shows the basic idea of the proposed solution. In the first part of the rotary kiln (calcination zone), where the surface temperatures are highest, the recuperator is set to preheat air. The amount of the heat that would be waste to the surroundings, in case that the recuperator does not exist, is used to preheat air.

After passing through the concentric annular, the preheated air is transported by the blower to the burner.

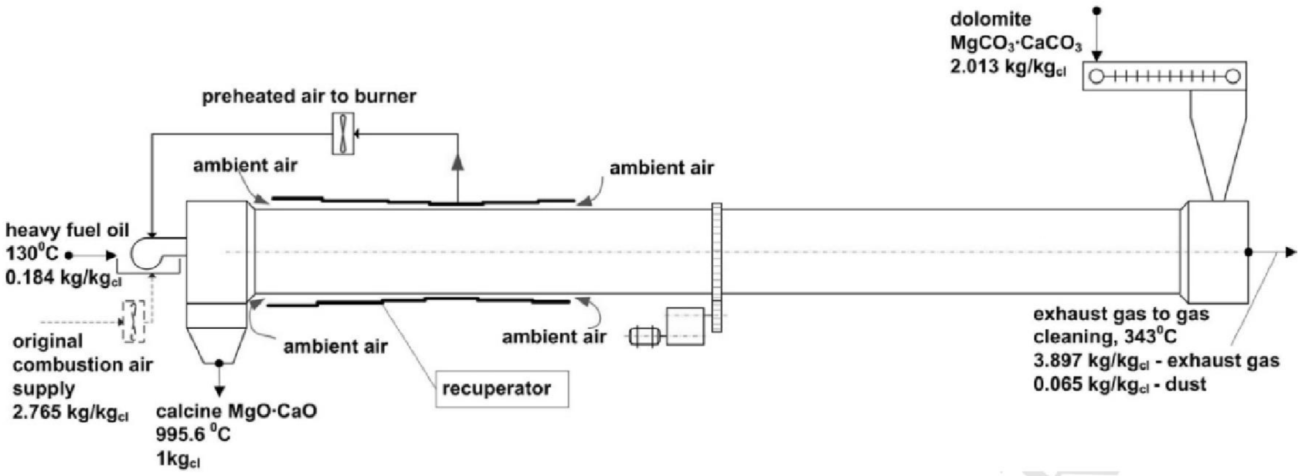

Figure 4.1 Schematic view of a rotary kiln and recuperator

5. MATHEMATICAL MODEL

A mathematical model that gives the geometry of the recuperator is developed. The model is based on the requirement that heat loss, due to external cooling of the kiln, is used to preheat the air [1].

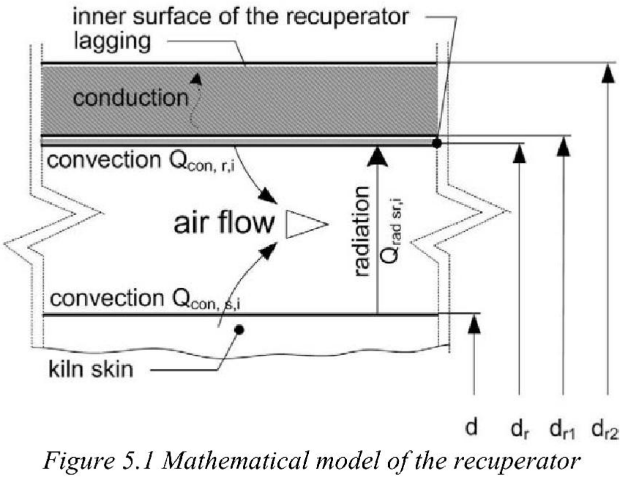

Figure 5.1 Mathematical model of the recuperator

Figure 4.1 shows changes of the recuperator diameter by sections. The preheated air is extracted approximately in the middle of the recuperator. Actually, preheated air is extracted over the section of the rotary kiln with the highest temperature.

As the surface temperature of the rotary kiln changes along it, and equal amount of air flows along each section to extract the heat from each section of the kiln equal to the heat loss from the bare kiln; the recuperator diameter changes in each section. Figure 5.1 shows the principle of the model used for diameter calculation and the temperature of preheated air. Two energy balance equations (5.1) and (5.2) are used:

$$\dot{Q}_{convs,i} + \dot{Q}_{convr,i} = \frac{\dot{m}_a}{2} C_{p,a} \left(t_{aout,i} - t_{ain,i} \right), \qquad (5.1)$$

$$\dot{Q}_{radsr,i} = \dot{Q}_{convr,i} + 0.03\dot{Q}_{s,i}\,. \qquad (5.2)$$

Equation (5.1) represents the energy balance of the air that flowing through *i*-th section of the recuperator, where:

- $\dot{Q}_{convs,i}$ - the heat flow rate exchanged between the kiln and the air by convection, $\dot{Q}_{convr,i}$ the heat flow rate exchanged between the air and the recuperator by convection.
- $\dot{m}_a / 2$ - is a half of the mass flow used for the heavy oil combustion in the rotary kiln. The airflow is divided into two equal streams flowing from both ends of the recuperator,
- $t_{aout,i}, t_{ain,i}$ - are the temperatures of air at the inlet and at the outlet of the *i*-th section of the recuperator.

Equation (5.2) is energy balance per unit of time for the inner surface of the recuperator and states that one part of the radiant heat flow received from the outer surface of the kiln is transferred by convection to the air while the other is transferred to the surroundings by conduction through insulation of the recuperator. The thickness of the insulation and the outer diameter of the recuperator are determined from the adopted fact that 3% of the initial heat loss of the kiln is lost through the insulation of the recuperator ($0.03\ \dot{Q}_{s,i}$ in Equation (5.2)).

The total heat loss ($\dot{Q}_{s,i}$) from the *i*-th section of the recuperator is equal to the initial heat loss from the *i*-th section of the bare kiln, obtained by

$$\dot{Q}_{s,i} = \dot{Q}_{convs,i} + \dot{Q}_{radsr,i} \qquad (5.3)$$

where:

- $\dot{Q}_{convs,i}$ - the heat flow rate of the *i*-th section of the kiln transferred by convection to the air flowing through the concentric annular,
- $\dot{Q}_{radsr,i}$ - the heat flow rate of the *i*-th section of the kiln transferred by radiation from the outer surface of the kiln to inner surface of the recuperator.

The heat flow rate $\dot{Q}_{radsr,i}$ is obtained for the case of two concentric tubes [13] by

$$\dot{Q}_{radsr,i} = \frac{\sigma}{\frac{1}{\varepsilon_{s,i}} + \frac{A_{s,i}}{A_{r,i}}\left(\frac{1}{\varepsilon_{r,i}} - 1\right)} A_{s,i}\left(T_{s,i}^4 - T_{r,i}^4\right), \qquad (5.4)$$

where:

- $\varepsilon_{s,i} = \varepsilon_{r,i} = 0.8$ - the degrees of emissivity of the kiln surface and recuperator [8, 9],
- $T_{s,i}, T_{r,i}$- the temperatures on *i*-th section of the kiln and recuperator,
- $A_{s,i}, A_{r,i}$- the areas on *i*-th section of the kiln and recuperator.

The model given in [10] that calculates the heat transfer in the concentric annular ducts for fully developed turbulent flow is used to obtain the heat flow rate by convection on the *i*-th sections of the kiln $\dot{Q}_{convs,i}$ and the recuperator $\dot{Q}_{convr,i}$. In the model, dimensionless numbers for *i*-th section of the recuperator $Nu_i = \frac{\alpha_i d_{h,i}}{\lambda}, Re_i = \frac{w_i d_{h,i}}{\nu}$ are determined by the use of the hydraulic diameter given by

$$d_{h,i} = d_{r,i} - d, \qquad (5.5)$$

where:

- $d_{r,i}$ - the inner diameter of the *i*-th section of the recuperator,
- d - the outer diameter of the rotary kiln.

It is important to note that the physical properties relate to the mean temperatures of the air.

$$t_{a,m} = (t_0 + t_p)/2, \qquad (5.6)$$

where:

- t_0- the temperature of ambient air,
- t_p- the temperature of preheated air.

For fully developed turbulent flow Re >10^4 in the concentric annular duct, the modified equation of Petukhov and Kirilov [11], is used [11]:

$$N_{u_{m,i}} = \frac{\left(\xi_{ann,i}/_8\right) \cdot R_{e,i} \cdot P_{r,i}}{k_{1,i} + 12.7 \cdot \sqrt{\xi_{ann,i}/_8} \cdot \left(P_{r,i}^{2/3} - 1\right)} \cdot \left[1 + \left(\frac{d_{h,i}}{l_i}\right)^{2/3}\right] \cdot F_{ann,i}, \qquad (5.7)$$

where:

$$k_{1,i} = 1{,}07 + \frac{900}{R_{e,i}} - \frac{0{,}63}{\left(1 + 10 \cdot P_{r,i}\right)} \qquad (5.8)$$

The friction factor ξ_{ann} depends on the ratio $a_i = d/d_{r,i}$ and is obtained by [10]

$$\xi_{ann,i} = \left(1{,}8 \cdot log_{10}\left(R_{e,i}^*\right) - 1{,}5\right)^{-2} \qquad (5.9)$$

where:

$$R_{e,i}^* = R_{e,i} \cdot \frac{\left[1 + a_i^2\right] \cdot \ln a_i + \left[1 - a_i^2\right]}{\left[1 - a_i^2\right] \cdot \ln a_i} \qquad (5.10)$$

For the boundary condition "heat transfer to the inner wall, the outer wall is insulated", which is valid for the examined recuperator, $F_{ann,i}$ in Equation (5.7), is obtained from [10] by

$$F_{ann,i} = 0{,}75 \cdot a_i^{-0.17} \quad (5.11)$$

Equation (5.7) which calculates the Nusselt number is modified by the use of the correction factor that includes the variation of fluid properties with temperature [10]:

$$K_i = \left(\frac{T_{a,m,i}}{T_{r,i}}\right)^{0.45}, \quad (5.12)$$

The presented model enables determination of the preheated air temperature, the temperature of the inner wall and the diameter in each section of the recuperator. The temperature at the outer surface of the *i*-th section of the recuperator is obtained by

$$0.03\,\dot{Q}_{s,i} = \frac{T_{r2,i} - T_0}{\frac{1}{2\pi\lambda_{steel}} ln\frac{d_{r1,i}}{d_{r,i}} + \frac{1}{2\pi\lambda_{insulation}} ln\frac{d_{r2,i}}{d_{r1,i}}} \quad (5.13)$$

Equation 5.13 is a well-known equation for one-dimensional steady state heat conduction through the tube wall, in which $\lambda_{steel} = 48\ W/mK$ and $\lambda_{insulation} = 0.041\ W/mK$ are thermal conductivities of the steel mantle and thermal insulation (mineral wool) over the annular duct. Equation 5.13 uses the already mentioned fact that the 3% of the initial heat loss from the bare kiln is transferred to the surroundings through the recuperator insulation.

6. MODEL FOR DETERMINATION OF THE INNER DIMENSIONS OF THE RECUPERATOR

Based on the examined model and determination of mass and heat balance of the rotary kiln, the temperatures of the inner and outer surface, dimensions and other parameters for each section of the recuperator are obtained. The calculations for these models are very complex because the mathematical model includes a large number of interactions.

For the simple resolving of exact mathematical model, the special program is developed for determination of the recuperator dimensions and temperatures at the inner and outer surface. The program obtains the curve of change of the recuperator diameter where the mantel of the recuperator is divided into smaller and equal sections. With this, the basic calculation model is improved and other parameters can be tested. Based on the improved calculation, the recuperator parameters are determined in the case when enriched air is used for the combustion in the kiln.

The use of the developed model is not limited only to this kiln and it can be used for other cylindrical surfaces.

7. MASS AND ENERGY BALANCE OF THE KILN SUPPLIED WITH ENRICHED AIR

At the kiln for dolomite calcination, measurements are carried in case where enriched air is used for combustion. The equivalent or additional enrichment is used for the air enriching. In this case, equivalent enrichment is used in the range of 21.5% to 23%, with the step of 0.5%. The determined results are shown in the tables below.

Table 7.1 Mass balance of the kiln with different percentages of enriched air.

	Mass flows	O_2 (%)				
	kg/kg$_{cl}$	21	21.5	22	22.5	23
Input	Raw material	2,013	2,013	2,013	2,013	2,013
	Fuel	0,184	0,184	0,184	0,184	0,184
	Air	2,765	2,654	2,593	2,536	2,481
	Total	4,962	4,851	4,790	4,733	4,678
Output	Calciner	1	1	1	1	1
	Exhaust products	3,897	3,786	3,725	3,668	3,613
	Dust	0,065	0,065	0,065	0,065	0,065
	Total	4,962	4,851	4,790	4,733	4,678

Table 7.2 Energy balance of the kiln with different percentages of enriched air.

Heat inputs	O_2 (%)	21		21,5		22		22,5		23	
		kJ/kgcal	%	kJ/kgcal	%	kJ/kgcal	%	kJ/kgcal	%	kJ/kgcal	%
Combustion of fuel (Q_1) - LHV		7435,44	98,96	7435,44	98,97	7435,44	98,98	7435,44	98,98	7435,44	98,99
Sensible heat of fuel (Q_2)		41,07	0,55	41,07	0,55	41,07	0,55	41,07	0,55	41,07	0,55
Sensible heat of air (Q_3)		22,25	0,30	21,36	0,28	20,87	0,28	20,41	0,27	19,96	0,27
Sensible heat of the feed (Q_4)		14,82	0,20	14,82	0,20	14,82	0,20	14,82	0,20	14,82	0,20
Total:		7513,58	100,00	7512,68	100,00	7512,20	100,00	7511,73	100,00	7511,29	100,00
Heat outputs	O_2 (%)	21		21,5		22		22,5		23	
Sensible heat of exhaust gas (Q_5)		1423,01	18,94	1348,11	17,94	1303,85	17,36	1258,70	16,76	1221,06	16,26
Sensible heat of calcine (Q_6)		1003,56	13,36	1003,565	13,36	1003,565	13,36	1003,5648	13,36	1003,565	13,36
Heat of formation of calcine (Q_7)		3023,35	40,24	3023,352	40,24	3023,352	40,25	3023,352	40,25	3023,352	40,25
Sensible heat of dust (Q_8)		19,66	0,26	19,66	0,26	19,66	0,26	19,66	0,26	19,66	0,26
Heat of decarbonization of dust (Q_9)		15,12	0,20	15,12	0,20	15,12	0,20	15,12	0,20	15,12	0,20
Moisture associated with feed (Q_{10})		48,01	0,64	48,01	0,64	48,01	0,64	48,01	0,64	48,01	0,64
Total heat loss to surroundings (Q_{11})		1980,87	26,36	2054,88	27,35	2098,65	27,94	2143,34	28,53	2180,53	29,03
Total:		7513,58	100,00	7512,68	100,00	7512,20	100,00	7511,73	100,00	7511,29	100,00

Table 7.3 Fuel saves by the use of the recuperator with different percentages of enriched air

O_2 (%)	21		21.5		22		22.5		23	
	kJ/kgcal		kJ/kgcal		kJ/kgcal		kJ/kgcal		kJ/kgcal	
Total input energy	7513,58		7512,68		7512,20		7511,73		7511,29	
Temperature of the heated air	299,60	C	313,50	C	322,10	C	333,20	C	341,90	C
Specific heat capacity of the heated air	1,0453	kJ/kgK	1,0484	kJ/kgK	1,0504	kJ/kgK	1,0529	kJ/kgK	1,0549	kJ/kgK
Physical heat of the heated air	865,91	kJ/kgcal	872,18	kJ/kgcal	877,37	kJ/kgcal	889,59	kJ/kgcal	894,69	kJ/kgcal
Fuel consumption with use of the recuperator	0,1632	kg/kgcal	0,1631	kg/kgcal	0,1629	kg/kgcal	0,1626	kg/kgcal	0,1625	kg/kgcal
Fuel saves	0,0208	kg/kgcal	0,0209	kg/kgcal	0,0211	kg/kgcal	0,0214	kg/kgcal	0,0215	kg/kgcal
Saves percentage	11,28	%	11,38	%	11,46	%	11,63	%	11,70	%
Amount of fuel saves	2192,06	kg/day	2210,66	kg/day	2225,42	kg/day	2258,38	kg/day	2272,77	kg/day

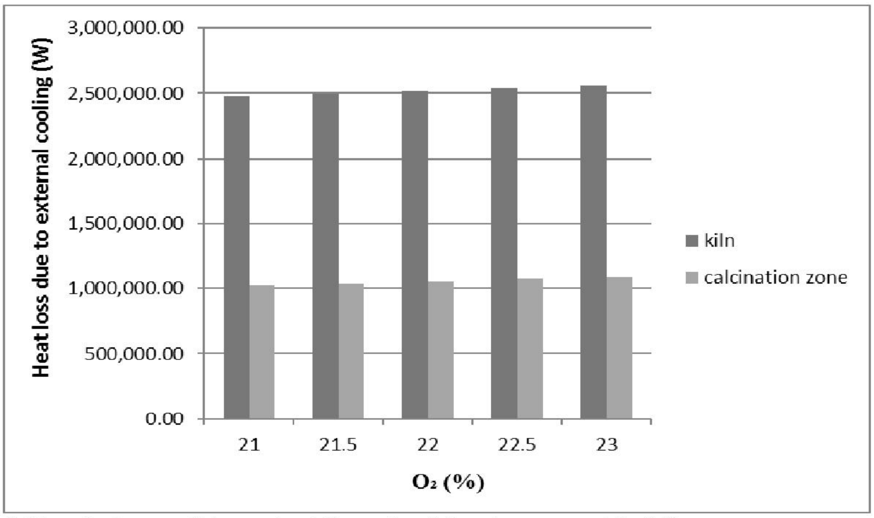

Figure 7.1 Heat balance of the entire kiln and calcination zone with different percentages of oxygen

8. RESULTS

The measured values of the temperature on the mantle of the kiln at various percentages of oxygen are approximated with the polynomial function of the fifth degree:

$$t = B_0 + B_1 \cdot l + B_2 \cdot l^2 + B_3 \cdot l^3 + B_4 \cdot l^4 + B_5 \cdot l^5 \quad (8.1)$$

Table 8.1 Polynomial functions of temperature.

O_2 (%)	B_o	B_1	B_2	B_3	B_4	B_5
21	321,997726	7,18033	-6,71522	1,84127	-0,17576	0,005250
21.5	325,875640	7,21080	-6,69770	1,83900	-0,17570	0,005250
22	329,597560	7,23120	-6,70552	1,84050	-0,17580	0,005251
22.5	332,287569	7,18947	-6,69980	1,83940	-0,17572	0,005250
23	336,589742	7,27050	-6,71860	1,83899	-0,17570	0,005252

Table 8.2. The mass flow rate of air entering the recuperator at various percentages of oxygen (half of the total mass flow rate)

O_2 (%)	21	21.5	22	22.5	23
$\frac{\dot{m}_v}{2}$ (kg/s)	1.6894	1.6213	1.5844	1.5492	1.5155

Figure 8.1 shows the recuperator diameters at various percentages of enrichment.

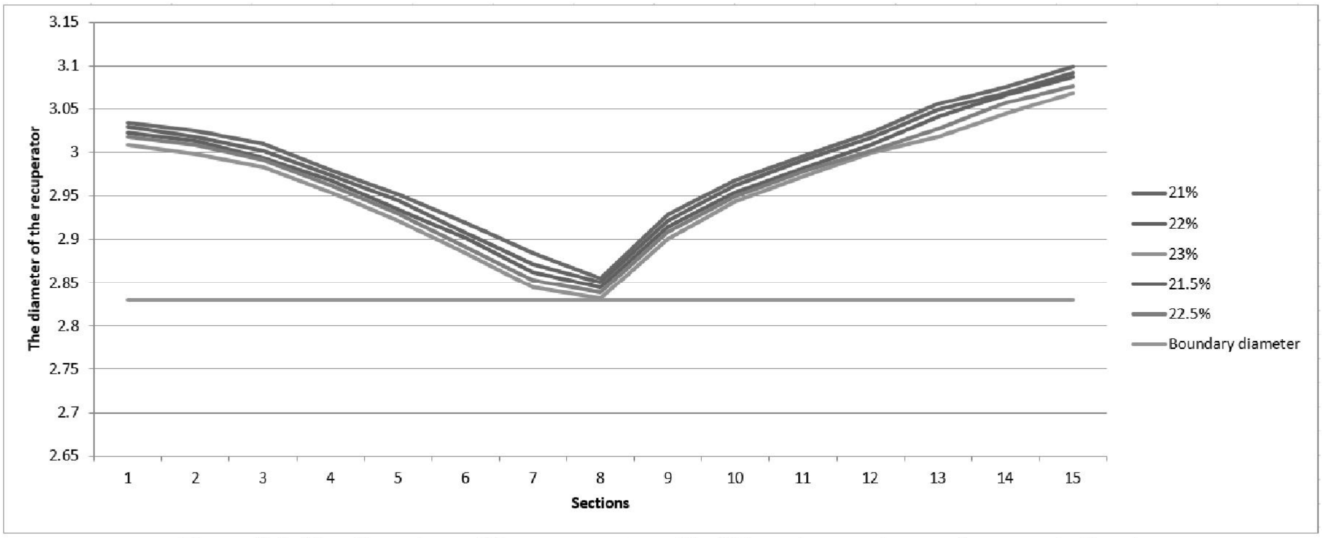

Figure 8.1. The diameters of the recuperator with different percentages of oxygen in the air

9. CONCLUSION

With the increase of oxygen in the air for combustion, the temperatures at the mantle of the kiln and the heat loss due to external cooling increase. This loss of heat is recycled through the recuperator, which changes dimensions according to the different enrichment of the air. The heat recuperation is carried in the calcination zone where the temperatures are highest.

The diameter of the recuperator decreases with the increase of oxygen in the air. Figure 8.1 shows that the mathematical model cannot be applied for further enrichment (over 23% of oxygen). In the case that enriched air has 23% of oxygen, the diameter of the recuperator, per value, is very close to the diameter of the kiln. The diameter of the kiln is 2.8m, but for the smooth functioning the smallest diameter of the recuperator is 2.83m.

For the enrichment of over 23% of oxygen, the recuperator cannot be applied and it is necessary to consider different ways of using heat from the mantle of the kiln. The developed mathematical model for dimension determination, presented in this paper, can be applied to other smaller or larger kilns.

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