ENERGY OPTIMISATION OF VERTICAL SHAFT KILN OPERATION IN THE PROCESS OF DOLOMITE CALCINATION

by

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The essential part of the refractory materials production on a basis of sintered dolomite as raw material is the process of dolomite calcination. The technology process usually takes place in shaft or rotary kilns, where the dolomite stone, $CaMg(CO_3)_2$, is subjected to a high temperature heat treatment. The calcination of the dolomite is highly endothermic reaction, requiring significant amount of thermal energy to produce sintered dolomite (CaO, MgO), generating a large flow of hot gases at the furnace outlet. The objective of this work was to assess the possibilities of utilization of waste heat of exhaust gases from a shaft kiln in order to improve the overall energy efficiency of the technology process. Several different options were analyzed: (a) preheating of a raw material, (b) preheating of heavy fuel oil, (c) preheating of combustion air, (d) preheating of combustion air and raw material with flue gas, and (e) preheating of air for combustion and for drying of a raw material. Option (e) was selected as the most attractive and therefore it was analyzed in more details, showing significant annual energy savings and relatively short simple payback period on the investment.

Key words: *energy efficiency, shaft kiln, combustion, dolomite calcination, thermal energy recovery*

Introduction

Improving energy efficiency can be powerful tool for reducing energy consumption and environmental pollution and important for achieving sustainable economic development on regional and national level and wider [1]. Waste heat recovery in industry sector is of very high significance regarding the efforts towards energy efficiency improvements, reduction of energy costs and reduction of emissions with potential local and global harmful effects. General trends in the current research and development in the field of industrial furnaces technology are elaborated in [2]. A complex approach to reduce the specific energy consumption and CO_2 emissions at a typical industrial facility is presented in [3]. The paper aims to investigate, by means of modeling the batch and cullet preheating option at a conventional natural gas fired container glass furnace, the different operating and design configurations on specific energy consumption, CO_2 emissions, flue gas energy recovery, batch temperature and preheater efficiency. Expected energy savings margin is estimated to 12-15%.

The non-metal industry is known due to the high energy intensity processes and as one of the larger contributors to the GHG emission. For instance, the cement industry contrib-

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utes with about 5% to global anthropogenic CO_2 emissions, and is thus an important sector in CO_2 emission mitigation strategies [4]. The CO_2 is emitted from the calcination process of limestone, from combustion of fuels in kilns, and from the fuel combustion during power generation, so that the strategies to reduce the CO_2 emissions include energy efficiency improvement as one of the main options.

Thermal energy analysis of three zones of a lime production process – preheating, calcination and cooling zone, is performed in the work [5]. The results indicate that increasing the residence time inside each zone will enhance thermal efficiency and reduce fuel consumption. The amount of thermal energy that is required in shaft kiln for the chemical reaction of dolomite calcination, accounts for an important part of the energy cost. Therefore, energy efficiency assessment of the calcination process is a fundamental aspect of the optimisation of sintered dolomite production. This is one of the crucial challenges with respect to the process control optimisation in order to reduce production costs [6].

Senegacnik *et al.* [7] presents a case of a remodeled annular shaft kiln, in which the excess air ratio can be reduced to its optimal level by re-circulation of waste flue gas and its injection into the combustion chambers. This also reduces stack loss, while the temperature profiles in the combustion chamber remain within the permissible range, which means that the specific energy consumption for lime burning is reduced. A new way to evaluate the energy performances of lime shaft kilns is proposed in the work [8]. Two new exergy-based indicators are introduced for the evaluation, one to assess the exergy efficiency of lime kilns and the other indicator to assess the effectiveness of the exergy consumption of the dissociation reaction. The combination of both indicators provides a clear picture of the energy performance of the process. The validity of the proposed assessment approach is examined using operating data measured in a commercial plant. Gutierrez *et al.* [9] proposes a tool for the analysis of energy and exergy utilization of the calcination process in vertical shaft lime kilns and also provides some energy conservation measures. Aiming to improve the thermal performance, a comprehensive energy and exergy analysis of a shaft kiln with opposite burners has been conducted in the work [10], based on actual operational data obtained from on-site measurements. The work incorporates the considerations of the moisture and magnesium carbonate content in the limestone and attempts to identify major sources of energy and exergy dissipation in the facility. Several measures for efficiency enhancement are proposed and the potential energy savings are estimated.

The cleaner production concept in general, including energy high demanding industries, such as lime processing, aims at increasing the efficiency, profitability and sustainability of the process and at decreasing its environmental impact with reduction of the process emissions, at the source rather than by end-of-pipe treatment [11]. A complex mathematical model for dynamic process simulation of limestone calcination in shaft kilns has been developed and used for process optimisation in the work [12]. A detailed environmental impact assessment of the operation of a lime kiln is presented in [13].

Piringer [14] compare the advantages of modern shaft kilns with other kiln models, shows new innovative ideas and explains in which areas further research and development is still required in order to meet the growing market demands, as well as energy efficiency and environmental protection requirements. In industrial practice, lime shaft kilns are usually considered as a black box because internal measurements are extremely difficult to conduct. Even simple thermocouple measurements, as presented in [15], are a challenge under the harsh high temperature condition of a dense limestone bed. Combined with a comprehensive CFD model with incorporated discrete element method, the research leads to a better under-

standing and optimization of the thermo-chemical processes inside lime shaft kilns, including parallel flow regenerative kilns.

For the sintered dolomite production, the primary target of optimisation is to decrease fuel consumption and the related environmental impact, including the release of greenhouse gases (particularly CO_2). Heat recovery solution in a particular segment of an industrial process is very often a specific engineering challenge, not only because of the expected energy savings, but also due to potential consequences (deviations) on the related technological processes and due to possible high investment costs related to delicate design and construction. Therefore, additional criteria have to be strictly observed and fulfilled, such as prescribed and uniform product quality, compliance with safety standards, stability of the processes etc. In that direction, the objective of the present work was to assess the performance of a vertical shaft kiln, in order to identify the main factors affecting the thermal efficiency and their influence on the fuel consumption. The main goal was to assess the possibilities of utilization of flue gas waste heat by implementation of relatively simple, easily feasible, economically effective technical solutions for energy consumption reduction, without affecting the calcination process. In order to perform a quantitative estimation, the kiln system was subjected to energy analysis using mass and energy balance equations. Five options for energy efficiency enhancement of shaft kilns have been considered in accordance to the recommendations given in [16-18] and the most attractive one is presented in this work.

Materials and methods

Dolomite is a carbonate mineral composed of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), theoretically in a portion 1:1 of their molecules, $CaMg(CO_3)_2$. The term is also used to describe the sedimentary carbonate rock dolostone [19]. High quality dolomite contains 57-60% $CaCO_3$ and 40-43% $MgCO_3$, but it usually contains impurities, chiefly silica, alumina and iron oxides, which should not go beyond 7%, since otherwise it becomes unsuitable for industrial use, mostly for metallurgical, chemical and building industries.

Description of the technology process in shaft kiln

The calcination of dolomite stone, which is one of the main stages of the sintered dolomite manufacturing, is chemical process which proceeds in a vertical shaft or rotary kiln. When heated, the dolomite decomposes according to the following endothermic reaction:

$$CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2 - Heat \tag{1}$$

$$1 \text{ kg } CaMg(CO_3)_2 \rightarrow 0.5227 \text{ kg } (CaO + MgO) + 0.477 \text{ kg } CO_2 - 1674 \text{ kJ/kg } CaMg(CO_3)_2 \tag{2}$$

$$1.913 \text{ kg } CaMg(CO_3)_2 \rightarrow 1 \text{ kg } (CaO + MgO) + 0.913 \text{ kg } CO_2 - 3202 \text{ kJ/kg } (CaO + MgO) \tag{3}$$

Decomposition takes place in two stages, starting at approximately 550 °C for the $MgCO_3$ portion and approximately 810 °C for $CaCO_3$ [18, 20]. Dolomite decomposes completely above 900 °C. In order to fully calcine the stone and to have no residual core, heat applied to the stone surface must penetrate via conductive heat transfer to the core. A temperature of 900 °C has to be reached in the core at least for a short period of time, since the atmosphere inside the material is pure CO_2. The stone surface must be heated to a temperature higher than 900 °C to maintain the required temperature gradient and overcome the insulating effect at the calcined material and the stone surface. The product resulting from this relatively low temperature calcination is highly porous and reactive and is known as *calcinated dolo-*

mite. Dolomite is sometimes used both in the raw and calcined form, as refractory material for hearth maintenance and for banking door in open hearth furnaces.

For most refractory uses, it is desirable to subject the dolomite to a heat treatment at very high temperatures, to shrink the material thoroughly and render it less reactive. The small crystals of MgO grow larger and the pores in the structure disappear. The bulk density may increase from around 1600 to over 3100 kg/m³. The resulting material is known as sintered dolomite or dead burned dolomite. Sintered dolomite is generally used as a base material for production of dolomite refractory bricks and a wide range of monolithic and gunning materials. These are used principally in the steel industry, but also in kilns for manufacturing of lime, dolomite lime and cement.

A dolomite shaft kiln is basically a moving bed reactor with upward flow of hot gases, passing counter-current to the downward-flow of a feed consisting of dolomite particles (15 to 60 mm) undergoing calcination. The dolomite stone is charged at the top and is calcinated as it descends slowly to discharge at the bottom of the kiln. While moving downwards, the dolomite passes through three operating zones:
(a) preheating,
(b) reaction, and
(c) cooling zone, fig. 1.

The preheating zone is the part of the kiln where the dolomite is heated to its dissociation temperature. The reacting (calcination) zone is a part of the kiln where the fuel combustion process and the process of calcination of dolomite takes place. The fuel required for the process is introduced through radially arranged burner lances, fig. 2, situated on two levels. This ensures evenly distribution of fuel and air and flexibility in adjusting the temperature profile to the requirements of the specific feed material and the required product quality. The cooling zone is that part of the kiln in which the sintered dolomite emerging from the reaction zone is cooled before discharge from the bottom of the kiln.

Figure 1. Schematic presentation of vertical shaft kiln;
(a) preheating zone,
(b) reacting zone, and
(c) cooling zone

Figure 2. Photographic display of the burner system

The calcination or burning of dolomite is highly endothermic reaction, requiring about 3202 kJ of heat input to produce one kg of sintered dolomite (CaO, MgO). The reaction only begins when the temperature is above the dissociation temperature of the carbonates in the dolomite. Once the reaction starts, the temperature must be maintained above the dissociation temperature, and CO_2 evolved in the reaction must be removed. Dissociation of the dolomite proceeds gradually from the outer surface of the particles inward, and porous layers of calcium and magnesium oxides, the desired products remain. The final product of the kiln, the sintered dolomite, is subjected to further processing.

In general, the shaft kilns have relatively low heat use rates, because of the efficient heat transfer process between the gases and the packed bed. Traditional shaft kilns operate continuously and are fired with liquid fuel introduced into the calcining zone, figs. 3 and 4 [21, 22].

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The main chemical reactions and energy use in a typical shaft kiln are presented in fig. 3. Figure 4 shows the temperature profiles of dolomite surface and gases in the preheating, reacting, and cooling zones, along the kiln height. In the preheating zone dolomite is heated from ambient temperature to its dissociation temperature, approximately 500 °C, by direct contact with gases leaving the calcining zone. In this zone, also, the process of evaporation of water in dolomite takes place.
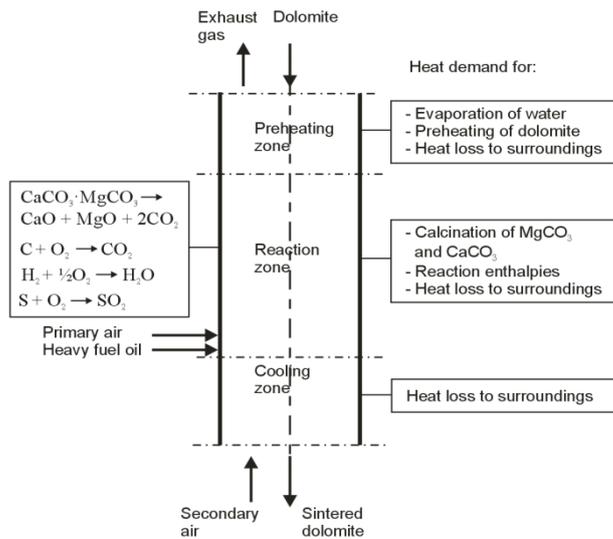
Figure 3. Main zones, chemical reactions, and energy use in a shaft kiln [21, 22]
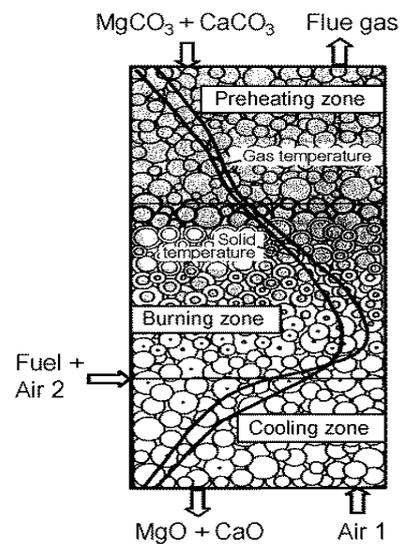
Figure 4. Zones and temperature profiles in the shaft kiln

The combustion process of fuel produces flue gas that reaches maximum temperature above 1600 °C and heats up the dolomite particles to a temperature sufficiently high to enable proceeding of the calcining process of $CaCO_3$ and $MgCO_3$. The fuel combustion process within the packed bed in vertical kiln is particularly complex, as mixing of fuel and air under these conditions is difficult. Heavy oil is an excellent fuel for kilns owing to its combustion products high emissivity, which results in high rates of heat transfer to the charge. However, to burn it efficiently, it must be atomized and sprayed in to the kiln in a controlled manner. The major problem is obtaining uniform heat release at movement of the burden across the shaft. Fuel injected at the wall usually does not penetrate more than one meter into the packed bed, that limits the kiln effectiveness and the kiln diameter to about 2 m and thus restricts the productive capacity of the kiln.

Kiln geometry and basic technical data

The main geometry data of the kiln are given in tab. 1 [21, 22]. The main data defining the kiln capacity are: the raw material (dolomite) consumption is 6.7 tones per hour and the sinter dolomite production is 3 tones per hour. The kiln operates in average about 7300 h per year. Heavy oil consumption is about 375-400 L per hours or 125-133 L per ton of sintered dolomite. Heavy oil enters the kiln at temperature of 130-140 °C. Total air volume flow rate entering the kiln is 6850 m^3 per hour, out of which 2950 m^3 per hour as primary and 3900 m^3 per hour as secondary air.

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Table 1. Basic geometry data of the kiln [21, 22]

Geometry parameter	Value
Total furnace height	9.69 m
Funnel cooling height	2.0 m
Height from the furnace bottom up to:	
(1) the first row of burners	3.79 m
(2) the second row of burners	4.99 m
Cooling zone height	3.79 m
Combustion zone height	2.3 m
Calcination zone height	8.1 m
Internal diameter	1.45 m
Thickness of the furnace insulation	0.8 m
External diameter	3.1 m

The raw dolomite composition is 54.3% $CaCO_3$ and 45.7% $MgCO_3$, with size range 18-60 mm, actual density 2800-2900 kg/m^3 and bulk density 1600 kg/m^3. Its temperature at the beginning of the calcination process is 400 °C. The composition of sintered dolomite, as final product, at the furnace outlet is ~60% CaO and ~39% MgO. The temperature of sintered dolomite at the furnace outlet is 60÷80 °C, while its density is 3.1-3.23 t/m^3 and the bulk density is 1.8-2.2 t/m^3. The average temperature of flue gases at the furnace outlet is 250 °C, further decreasing till the outlet channel to the chimney up to 135-190 °C. The quantity of CO_2 produced in the calcination process is 0.477 kg/kg dolomite (y_{CO_2} = 0.477 kg/kg).

Data for material and energy balancing

The presumed ultimate chemical composition of the used heavy fuel oil is: C = 84.4%, H = 10.0%, O = 0.8%, N = 0.5%, S = 1.0%, A = 0.3%, W = 3.0%. The stoichiometric (theoretical) amount of air required for complete combustion of the fuel oil is $M_{a,min}$ = 13.08 kg/kg fuel, *i. e.*, $V_{a,min}$ = 10.18 m$_n^3$/kg fuel. In order to determine the available gas waste heat energy, in the study were used measurements of temperature and mass flow of exhaust gas and processed material (tab. 2).

The excess air supplied in the kiln in the considered working mode is:

$$\lambda = \frac{V_{ap} + V_{as}}{V_{a,min} M_f} = 1.885 \qquad (4)$$

Table 2. Data used to establish material and energy balance [21, 22]

Parameter	Value
Mass-flow rate of dolomite stone entering the silo	M_{D1} = 6.7 *t/h* = 1.861 kg/s
Temperature of dolomite stone entering the silo	t_{D1} = 10 °C
Mass-flow rate of dolomite stone (after screening) entering the kiln	M_D = 6.03 *t/h* = 1.675 kg/s
Mass-flow rate of sintered dolomite at the kiln exit	M_{SD} = 3.015 *t/h* = 0.838 kg/s
Temperature of sintered dolomite at the kiln exit	t_{SD} = 105 °C
Volumetric flow rate and temperature of primary air	V_{ap} = 2,950 m$_n^3$/h, t_{ap} = 80 °C
Volumetric flow rate and temperature of secondary air	V_{as} = 3,900 m$_n^3$/h, t_{as} = 50 °C
Mass flow rate and temperature of fuel oil entering the kiln	M_f = 347 kg/h, t_f = 130 °C
Gas temperature and specific heat capacity at the end of the reaction zone	t_g = 570 °C, c_g = 1.2053 kJ/kgK
Temperature of the dolomite at the end of the reaction zone	t_D = 550 °C
Temperature and specific heat capacity of exhaust gas	t_{gi} = 220 °C, c_{gi} = 1.102 kJ/kgK
Average mass fraction of CO_2 per kg of dolomite	y_{CO_2} = 0.47 kg CO_2/kg dolomite
Heat loss through the walls of the kiln (assumed value)	q_o = 170 kJ/kg sin. dolomite

The mass-flow rate of flue gas is:

$$M_g = M_f(1 + \lambda M_{a,min}) + \frac{M_{SD} y_{CO_2}}{1 - y_{CO_2}} = \frac{357}{3600}(1 + 1.885 \cdot 13.08) + \frac{0.8375 \cdot 0.47}{1 - 0.47} = 3.287 \text{ kg/s} \qquad (5)$$

The amount of combustion products per kg fuel oil at excess air $\lambda = 1.885$ is $V_{RW} = 20.09$ m_n^3/kg and the average flue gas composition is:

$CO_2 = 22.84\%$, $SO_2 = 0.03\%$, $O_2 = 7.88\%$, $N_2 = 63.14\%$, $H_2O = 6.11\%$.

At previous conditions, the exhaust gas heat content is:

$Q_{gi} = M_g c_{gi} t_{gi} = 3.287 \cdot 1.102 \cdot 220 = 797$ kW.

The theoretical mass fraction of CO_2 in sintered dolomite is $z_{CO_2} = 0.913$ kg CO_2/kg sintered dolomite.

The specific energy consumption is $E_{sp} = 4,700.24$ kJ/kg sintered dolomite.

Calculated specific fuel consumption is $M_f/M_{SD} = 116.9$ kg fuel/t sintered dolomite.

Calculated fuel mass-flow rate is $M_f = 352.5$ kg/h.

Specific fuel consumption on a basis of data from the monitoring system is $M_f/M_{SD} = 118.4$ kg fuel/t sintered dolomite.

Energy balance of the reaction and cooling zones of the shaft kiln

The energy input and output flows in the reaction and cooling zones are schematically presented in fig. 5 [21, 22]. The energy balance equation for the reaction and the cooling zones of the furnace is:

Chemical energy of fuel + Physical energy of fuel + Energy in primary air +
+ Energy in secondary air + Energy in dolomite stone = Energy in sintered dolomite + 　　(6)
+ Reaction enthalpy of dolomite + Energy in exhaust gas + Energy loss to the surroundings

$$M_f H_d + M_f c_f t_f + M_{ap} c_{ap} t_{ap} + M_{as} c_{as} t_{as} + M_D c_D t_D = M_{SD} c_{SD} t_{SD} + M_{SD} \Delta H_{SD} \eta_c + M_g c_g t_g + Q_o \qquad (7)$$
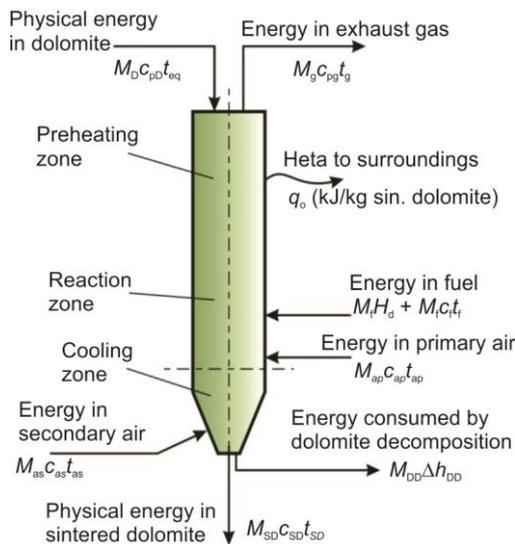
Figure 5. Graphical presentation of energy balance of the reaction and the cooling zones [21, 22]

The total air mass-flow rate in the furnace (in kg/s) is equal to the sum of the primary and the secondary air-flow rates:

$$M_a = M_{ap} + M_{as} = \lambda M_{a,min} M_f \qquad (8)$$

Taking that $(1 - x)$ [kgkg^{-1}] and x [kgkg^{-1}] are the mass fractions of the primary and secondary air, consequently, it:

$M_{ap} = (1 - x)M_a$ and $M_{as} = xM_a$.

Thus, the sum of the heat contained in primary and in secondary air is defined:

$$M_{ap} c_{ap} t_{ap} + M_{as} c_{as} t_{as} = (1-x)M_a c_{ap} t_{ap} + $$
$$+ xM_a c_{as} t_{as} = M_a \left[(1-x)c_{ap} t_{ap} + xc_{as} t_{as} \right] = \qquad (9)$$
$$= \lambda M_{a,min} M_f \left[(1-x)c_{ap} t_{ap} + xc_{as} t_{as} \right]$$

The exhaust gas mass-flow M_g [kgs^{-1}] consists of the air-flow, M_a, the fuel-flow, M_f, and the CO_2 flow produced by the calcination of dolomite ($M_D y_{CO_2}$):

$$M_g = M_a + M_f + M_D y_{CO_2} \qquad (10)$$

where M_D [kgs^{-1}] is mass-flow of dolomite and y_{CO_2} is the mass fraction of CO_2 in the dolomite, *i. e.*, $M_D - y_{CO_2} M_D = M_{SD}$:

$$M_D = \frac{M_{SD}}{1 - y_{CO_2}} \tag{11}$$

Substituting the eqs. (2) and (8) into eq. (6) gives:

$$M_g = \lambda M_{L/min} M_f + M_f + \frac{M_{SD}}{1 - y_{CO_2}} y_{CO_2} = M_f (1 + \lambda M_{a,min}) + \frac{M_{SD}}{1 - y_{CO_2}} y_{CO_2} \tag{12}$$

Substitution the eqs. (3), (8), and (9) into eq. (1) gives:

$$M_f H_d + M_f c_f t_f + \lambda M_{a,min} M_f \left[(1-x)c_{ap}t_{ap} + xc_{as}t_{as} \right] + \frac{M_{SD}}{1 - y_{CO_2}} c_D t_D = M_{SD} c_{SD} t_{SD} +$$

$$+ M_{SD} \Delta H_{SD} \eta_D + M_f (1 - \lambda M_{a,min}) c_g t_g + \frac{M_{SD}}{1 - y_{CO_2}} y_{CO_2} c_g t_g + Q_o \tag{13}$$

After rearranging the eq. (13), the following equation can be used to calculate the specific energy consumption in the furnace:

$$E = \frac{M_f H_d}{M_{SD}} = \frac{c_{SD}t_{SD} + \Delta H_{SD}\eta_D + \dfrac{y_{CO_2}}{1 - y_{CO_2}} c_g t_g - \dfrac{c_D t_D}{1 - y_{CO_2}} + \dfrac{Q}{M_{SD}}}{1 + \dfrac{c_f t_f}{H_d} + \dfrac{\lambda M_{a,min}}{H_d}[(1-x)c_{ap}t_{ap} + xc_{as}t_{as}] - (1 + \lambda M_{a,min})\dfrac{c_g t_g}{H_d}} \quad [\text{kJkg}^{-1} \text{ sin. dolomite}] \tag{14}$$

The previous relation is also used to estimate the specific fuel consumption M_f/M_{SD} [kg fuelkg^{-1} sin. dolomite] and the fuel mass-flow rate M_f [kgs^{-1}].

Specific energy and specific fuel consumption

By using eq. (14) and measured, assumed and calculated data, the specific energy and fuel consumption and fuel mass-flow rate can be calculated. The data used to calculate the energy consumption are presented in tab. 3 [21, 22].

After substituting the values from the kiln operation data in eq. (14), the calculated specific energy consumption is $E = 4700.2$ kJ/kg sintered dolomite.

Since the specific energy consumption is defined as $E = M_f H_d/M_{SD} = 4700.2$ kJ/kg sintered dolomite, the specific fuel consumption of the kiln is:

$m_f = M_f/M_{SD} = 4700.2/H_d = 0.1169$ kg fuel/kg sin. dol. = 116.9 kg fuel/t sin. dol.

The mass-flow rate of the fuel is:

$M_f = m_f M_{SD} = 0.1169 \cdot 0.8375 = 0.0979$ kg fuel/s = 352.5 kg/h.

From the statistical data, the following specific fuel consumption is obtained:
$m_f' = M_f'/M_{SD} = 347/3015 = 0.11509$ kg fuel/kg sin. dolomite = 115.1 kg fuel/t sin. dolomite.

Options for kiln efficiency improvement

Five options were analyzed in the framework of the study for energy efficiency improvement [21]:
(1) preheating of raw material,
(2) preheating of fuel,
(3) preheating of combustion (primary) air,
(4) preheating of combustion air and raw material with exhaust-gas, and
(5) preheating of air for combustion and for drying of raw material.

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Table 3. Data used to calculate the energy consumption [21, 22]

Parameter	Value
Sinter dolomite amount	$M_{SD} = 3015$ kg/h $= 0.8375$ kg/s
Sinter dolomite temperature	$t_{SD} = 100$ °C
Specific heat capacity of sinter dolomite	$c_{SD} = 1.065$ kJ/kgK
Temperature of (raw) dolomite	$t_D = 550$ °C
Specific heat capacity of raw dolomite	$c_D = 1.13$ kJ/kgK
Temperature of gas at the end of the reaction zone	$t_g = 570$ °C
Specific heat capacity of gas at $t_g = 570$ °C	$c_g = 1.205$ kJ/kgK
Primary air volume flow	$V_{ap} = 2950$ m_n^3/h
Secondary air volume flow	$V_{as} = 3900$ m_n^3/h
Ratio: secondary air / total air-flow	$x = V_{as}/V_a = 0.569$
Temperature and specific heat capacity of primary air	$t_{ap} = 80$ °C, $c_{ap} = 1.024$ kJ/kgK
Temperature and specific heat capacity of secondary air	$t_{as} = 50$ °C, $c_{as} = 1.023$ kJ/kgK
Stoichiometric air quantity	$M_{Lmin} = 13.08$ kg/kg,
Excess air	$\lambda = 1.885$
Reaction enthalpy of dolomite	$\Delta H_{SD} = 3202$ kJ/kg sint. dol.
Temperature of fuel (heavy oil)	$t_f = 130$ °C
Specific heat capacity of fuel	$c_f = 1.738 + 0.0025 t_f = 2.063$ kJ/kgK
Degree of calcination (conversion degree of dolomite)	$\eta_D = 0.98$

The option 5, utilization of exhaust gas energy for air preheating that will be partly used as combustion air and partly for drying and preheating of a raw material was assessed as most attractive one and has been analyzed in detail. A schematic presentation of this energy efficiency option is graphically presented in fig. 6 [21, 22].

Preheating of raw material is going to have several positive implications in the process: the dolomite stone will enter the kiln better dried and at higher temperature, introducing additional heat energy, which means, certain fuel saving will be achieved and the process will be improved. The processes of preheating and drying of the raw material is going to take part in the silo. The exhaust gas at assumed average temperature of 215 °C is introduced at the lower part of the silo and it leaves the silo at its upper end. A limiting factor of the gas temperature at the exit of the silo is the content of sulphure in the heavy fuel oil. When the temperature of the silo metal or gas channels is below the acid dew point, the process of low temperature corrosion is going to appear. To mitigate this process, the energy balance of the silo is done under the assumption that the exit gas temperature will not fall below 150 °C and, also, it is recommended to insulate all the metal channels and the silo.

The energy balance of the silo in the case of the option 5 is represented with the following general equation:

Energy content of dolomite at the silo exit − Energy content of dolomite at the silo inlet =
= (Energy content of the gas at the silo inlet − Energy content of the gas at the silo exit) ·   (15)
· Energy efficiency of the silo

$$M_D c_{D2} t_{D2} - M_D c_{D1} t_{D1} = (M_g c_{g1} t_{g1} - M_g c_{g2} t_{g2})\eta \qquad (15a)$$

The energy balance of the heat exchanger *exhaust gas-air* is given by:

Energy in primary air after heating − Energy in primary air before heating =
= (Energy in exhaust gas before heat exchanger − Energy in exhaust gas after heat exchanger) ·   (16)
· Heat exchanger efficiency
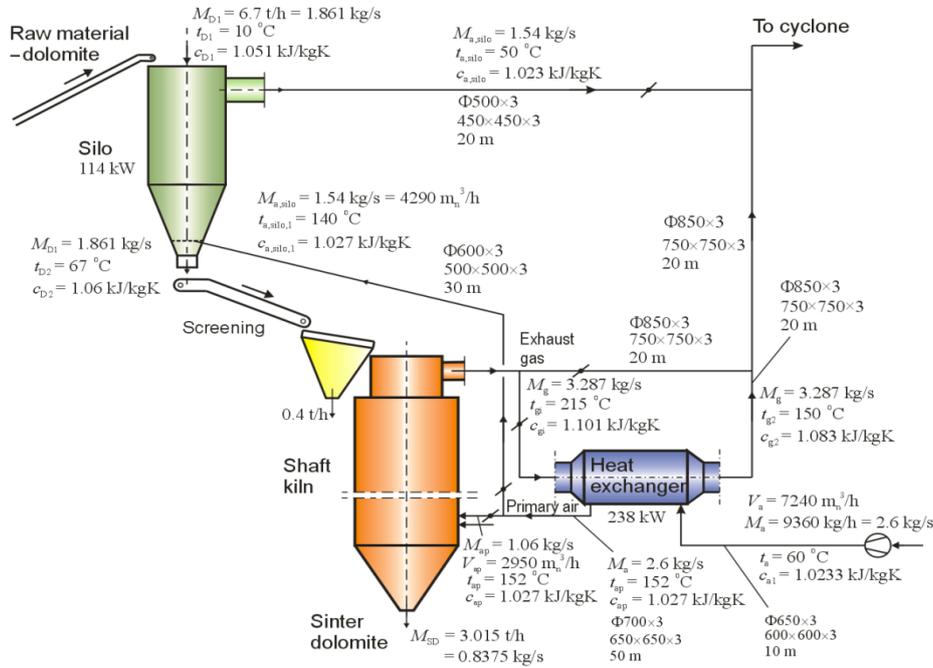
Figure 6. Schematic presentation of the option – utilization of exhaust gas energy for preheating of air that will be used for combustion and for drying of raw material [21, 22]

$$M_{ap}c_{a2}t_{a2} - M_{ap}c_{a1}t_{a1} = (M_g c_{g1}t_{g1} - M_g c_{g2}t_{g2})\eta \qquad (16a)$$

Results and discussion

Thermal power of the combustion (primary) air at common operating conditions is:

$$Q_{ap} = M_{ap}c_{a2}t_{a2} = (M_g c_{g1}t_{g1} - M_g c_{g2}t_{g2})\eta + M_{ap}c_{a1}t_{a1}$$
$$Q_{ap} = (3.287 \cdot 1.109 \cdot 215 - 3.287 \cdot 1.083 \cdot 150)0.95 + 2.6 \cdot 1.0233 \cdot 60 = 405.9 \text{ kW} \qquad (17)$$

The temperature of the combustion air will be:
$$t_{a2} = 405.9/M_{ap}c_{a2} = 405.9/2.6 \cdot 1.027 = 152 \text{ °C}.$$
Thus, from the energy balance of the silo:

$$M_D c_{D2}t_{D2} - M_D c_{D1}t_{D1} = (M_{a,silo}c_{a,silo1}t_{a,silo1} - M_{a,silo2}c_{a,silo2}t_{a,silo2})\eta$$

$$M_D c_{D2}t_{D2} = (1.54 \cdot 1.027 \cdot 140 - 1.54 \cdot 1.023 \cdot 50)0.8 + 1.861 \cdot 1.051 \cdot 10 = 133.7 \text{ kW} \qquad (18)$$

the temperature of dolomite stone at the exit of the silo is calculated:
$$t_{D2} = 133.7/1.861 \cdot 1.06 = 67.8 \text{ °C}.$$
Given the previous balances and calculations, the utilized energy with this measure is:

$$Q = (M_g c_{g1}t_{g1} - M_g c_{g2}t_{g2})\eta_g = (3.287 \cdot 1.1093 \cdot 215 - 3.287 \cdot 1.0825 \cdot 150)0.95 = 238 \text{ kW} \qquad (19)$$

The utilized share of the total fuel chemical energy entering the kiln is:

$$\frac{Q}{M_f H_d} = \frac{238}{0.09792 \cdot 40,200}100 = 6.05\% \qquad (20)$$

Under the assumption that the kiln operates $\tau = 7300$ hours per year, the annual energy saving with this energy efficiency option will be:

$$E = Q\tau = 7300 \cdot 238 = 1737400 \text{ kWh/year} \qquad (21)$$

which is equivalent to about 183 tons of heavy oil per year.

Based on the amount of the calculated fuel savings, at the current price of heavy oil of ~0.5 €/kg, the cost savings are estimated at about 91500 €/year.

The other four energy efficiency options have been analyzed in an analogous way as the option 5. The main outputs of the comparative analysis are presented in tab. 4 [21, 22].According to the specification prepared for the option 5, the main components necessary for its implementation comprise: heat exchanger *exhaust gas-air*, thermal power 250 kW, compressor: air-flow 2.6 kg/s, $p = 2$ bar, air-duct system, gas-duct system and auxiliary devices. The estimated length of separate sections of the air and gas channels is shown in fig. 6. The estimation of project implementation costs, based on actual situation in the production plant, indicates total amount of 132000 €. The project therefore has a favorable indicative simple payback period of less than 18 months. In addition, the project implementation would help improving environmental conditions by reduction of emissions of pollutants to the air.

Table 4. Main outcomes of the analyzed options [21, 22]

Option	Utilized heat [kW]	Energy saving [MWhyear^{-1}]	Fuel saving [tyear^{-1}]	Energy saving [%]
1 – Preheating of raw material	183.3	1283	135	4.7
2 – Preheating of heavy fuel oil	22	160	16.0	0. 6
3 – Preheating of combustion (primary) air	95	693.5	73	2.4
4 – Preheating of combustion air and raw material with off-gas	194	1416.2	149	4.9
5 – Preheating of air for combustion and for drying of raw material	238	1737.4	183	6.1

To improve the thermal efficiency, it is desirable to recover as much heat as possible from the flue gases. However, due to the sulphur content in the fuel oil and, therefore, SO_2 in the flue gas, which easily reacts with H_2O, resulting in sulphur acid (H_2SO_4), the flue gas temperature must not fall that much as to allow sulphur acid to condense on metal surfaces, causing low temperature corrosion. That is a frequent problem in industry and, very often, the main limiting factor in projects for waste heat recovery. The proposed system is therefore designed to ensure that flue gas temperature does not drop below the acid dew point for any extended period. In periods of low gas temperature, the gases should be diverted via by-pass directly to the cyclones.

The results of the analysis clearly suggest that, at the considered operating conditions, the total amount of air, primary and secondary, introduced into the shaft kiln is larger than it is necessary, based on the fuel-air stoichiometric ratio. This means that the technology process will run smoothly with significantly lower air-flow. The optimisation, *i. e.*, reduction of the air-flow rate would result with the following: reduction of the operating capacity of the air compressors and therefore reduced electricity consumption; decrease of thermal energy consumption needed to warm up the excess air; the same temperature profile will be obtained with reduced fuel consumption and reduced emissions to the air.

Conclusions

The objective of this work was to assess the possibilities for utilization of waste heat of exhaust gas from the shaft kilns for dolomite thermal processing. In this case, the heat recovery solution was a specific engineering challenge, due to the expected energy savings, but also due to potential deviations on the related technological process and because of the constraints imposed by the characteristics of the fuel used. It is found that there is a relatively large amount of waste heat in the exhaust gases of the shaft kilns, but relatively low temperature and presence of sulphure in the used fuel are constraining factors for a waste heat recovery project. Five different options were analyzed:

(1) preheating of a raw material,
(2) preheating of fuel-heavy oil,
(3) preheating of combustion air,
(4) preheating of combustion air and raw material with flue gas, and
(5) preheating of air for combustion and for drying of a raw material.

The option (5) was selected as the most attractive from energy efficiency, financial and environmental viewpoint and therefore it was analyzed in more detailed manner. The analysis has shown that this is relatively simple, easily feasible, economically effective technical solution for energy consumption reduction, without affecting the calcination process. According to the calculations, the annual energy saving would be 1737.4 MWh/year, or transformed to equivalent heavy fuel oil, about 183 tons per year. At the present fuel prices in the country, that is a cost saving of about 91500 €/year. The simple payback period on investment for this option, without purchasing new compressor units, which would be the highest item in the specification list, is less than one and a half year.

Nomenclature

c – specific heat capacity, [$\text{kJkg}^{-1}\text{K}^{-1}$]
E – energy consumption (sintered dolomite), [kJkg^{-1}]
H – enthalpy, [kJkg^{-1}]
H_d – lower (net) heating value, [kJkg^{-1}]
M – mass-flow, [kgs^{-1}]
Q – heat-flow, [kJs^{-1}]
q – specific heat, [kJkg^{-1}]
q_o – heat loss to the surroundings (sintered dolomite), [kJkg^{-1}]
t – temperature, [°C]
V – volumetric flow, [$\text{m}_\text{n}^3\text{h}^{-1}$]
V_RW – amount of combustion products per kg fuel, [m^3kg^{-1}]
y – actual mass fraction per kg dolomite
z – theoretical mass fraction per kg dolomite
ΔH_SD – reaction enthalpy of dolomite, [kJkg^{-1}]

Greek symbols

λ – excess air coefficient
ρ – density
η – efficiency, conversion degree
η_D – degree of dolomite calcination

Subscripts

a,min – stoichiometric air
ap – primary air
as – secondary air
c – combustion, conversion
D – dolomite
f – fuel
g – gas, flue gas
o – ambient, surroundings
RW – moist combustion products
SD – sintered dolomite

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