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Energy consumption and CO_2 and NOx emissions minimised in an intermittent ceramic kiln – "ECONOMICK kiln"

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Abstract. ECONOMICK LIFE project developed an innovative shuttle kiln for ceramic production, which consumes about 47% less energy than actually existing ones and, so, allows the industry to reduce costs, CO_2, NOx, HF, SOx and dust emissions, and raw materials. A patented technology is used to recover heat from flue gases to pre-heat combustion air. Significantly, this technology does not use flues or other pipes and above all does not alter the fluid dynamics of the flue gases in any way, which therefore remain identical to those of a traditional shuttle kiln. This advantage, with the possibility of adjusting the flame speed, is important as it optimises the flue gas/piece thermal exchange and does not affect either uniformity of firing or energy savings at low temperatures. This patented technology allows to use preheated combustion air and to reduce max temperature in the burner body, adjusting flame speed. Further, a specific software allows to preserve a preselected air/gas ratio and to use different values in function of the firing cycle. A careful selection of the refractory materials, resulting in a lining that minimises thermal inertia and at the same time allow a cool wall temperature of below 50°C.

1. Introduction

Industry is responsible for a huge part of greenhouse gases, especially the so-called energy-intensive industries. One of the most energy intensive industrial sectors is the ceramics industry. This sector consumes large amounts of energy during all its processes, but mainly during firing, which is responsible for 50-60% of the total energy consumed. Furnaces can reach very high temperatures that range between 800 and 1200 degrees Celsius, which requires a significant consumption of fossil fuels, mainly natural gas. The innovation proposed in this project, targets the entire ceramic sector except of tiles manufacturing, thus including about 50% of entire ceramic manufacturing (sanitaryware, tableware, ornamental ware, terracotta products). Considering that 2030 is less than the lifetime of a new kiln away, new technological approaches are urgently required to achieve the 2030 objectives and move timely on towards the objectives as defined in the Low-carbon economy Roadmap 2050. Reducing kiln energy consumption decreases energy costs and CO_2 emissions. On the other hand, owing to the EU legislation on emissions trading, CO_2 emissions can also entail an economic cost for companies. Thus, lowering thermal energy consumption decreases manufacturing costs and improves company competitiveness [1]. However, lower natural gas consumption means that better use is made of natural resources, thus contributing to international policies aimed at reducing fossil fuel consumption [2], following the roadmap to move to a competitive low carbon economy [3].

The ceramics industry uses tunnel kilns for continuous operation of large volumes, implying low flexibility in production, standard dimensions of pieces to be fired and lower energy costs (900-1500

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kcal/kg). Intermittent or shuttle kilns are used for discontinuous production, for low volumes, particular pieces, and refiring, with high energy costs (2100-2700 kcal/kg of fired pieces), and much flexibility [4-6]. Intermittent (or shuttle) kilns are used in about 50% of the ceramic sectors, excluding only tiles industry. Producers of sanitary and table ware, refractory or artistic ceramics use a shuttle kiln for refining ceramic artefacts with some defects, while smaller factories use such a kiln also for first firing, alternatively to a tunnel kiln that needs high production levels. Every factory for sanitaryware, tableware, artistic ceramics and terracotta floors is equipped with an intermittent kiln for firing or refiring and/or firing of decorum, while SMEs have only them. Technological solutions adopted actually are based on high-speed burners; computerized control of kiln management; recovery of heat from the kiln' cooling; fume extraction torch down (for intermittent kiln); and preheating combustion air (only for tunnel kilns). Some producers applied reuse of flue gases in intermittent kilns by introduction of flue gases in auto-regenerating burners, promising an energy consumption between 1500-2000 kcal/kg. Results held by end-users are though disappointing, as the technology appears to be constraint by varied technical problems, like:
- Difficult control of the kiln atmosphere (O_2/CO_2 contents)
- Reduced efficiency of the heat exchange due to altered flu-dynamics of the fumes
- Reduced turbulence of the fumes leading to a reduced heat exchange rate
- Foresaid problems lead to quality problems in the enamels
-The burners cannot be applied to existing furnaces as their dimension is much bigger than ordinary burners.

SE.TE.C.'s idea starts from the reuse of flue gases to heat the combustion air by heat exchangers that are not be inserted in the burners like competitors propose, avoiding above mentioned problems. A novelty in shuttle kilns that, about other technologies, can also be applied to existing furnaces. Instead, it aims to combine this novelty with several other innovations that want produce a shuttle kiln fully competitive with a tunnel kiln from an energy and cost perspective.

ECONOMICK comprises:
1. Integral reuse of the heat of the flue gas spread through the chimneys, obtained by heat exchanger outside the kiln
2. Innovative COEL burners, that can vary the speed of the combustion gas flow and the length of the flame, allowing to maximise heat exchange rate between fumes and fired pieces increasing notably the efficiency and performing the kiln and reducing NOx emissions up to 15%. This new burner has 2 entrances: 1 for combustion air and 1 for of dilution air that can be regulated by PLC to change the atmosphere of the furnace from highly to lowly oxidised, optimising kiln atmosphere and flame heat, reducing thermal NOx emissions emerging normally at high temperatures.
3. A fully computerized management of the air and gas flow, to have almost stoichiometric ratio of combustion, leading to a further minimization of thermal energy consumption;
4. Redesign of the structure of the kiln with reduced thermal dispersion. The insulation optimization is achieved by the design of the vault and walls as well as with the use of advanced materials with high performances.

In this paper we present the results obtained in the ECONOMICK project which included:
- Choice of insulating and refractory materials necessary for the construction of the combustion chamber and the kiln car. Thanks to a simulation program in which the data of the selected materials are inserted, the best compromise between thermal inertia and insulation was verified.
- The construction of the 9 m^3 ECONOMICK prototype, with the best thermal configuration, performed in the SE.TE.C. workshop.
- The prototype built in this way was equipped with probes and thermocouples for determining consumption and emissions and is moved to a ceramic company for its use in firing sanitaryware and tableware.
- During the production phase, thermal and electrical consumption and emissions into the atmosphere were measured in order to verify the difference with a direct comparison through a standard intermittent kiln.

In this article, we present the results of the simulation phase, verifying the prototype operation by thermal measurements and consumption that allowed us to compare the performances during firing.
A saving of 20% is because of the technical characteristics of the insulating and refractory materials, a 23% to the heat recovery through the exchanger and a 5% to the management and control of the burners through an oxygen probe.

2. Methods

2.1. Selection of optimal materials and use of SIMU-THERM simulation software
SE.TE.C technical staff (including engineers, technical designers, electricians and chief mechanic) select materials and parts and draft a list for each category, comparing prices and performances. The aim is to select the best materials and parts for construction of the prototype, on solid information schemes. Building an intermittent kiln comes from that in recent times companies prefer to invest in a furnace that allows them to have greater labor flexibility. The idea for the ECONOMICK project is born from these seeks by market of our customers. The prototype construction shuttle kiln with a volume of 9 m^3. It allows us to fulfill these new needs and, at the same time, to have an open-flame furnace carrying out the firing cycle in a day, even with fast firing cycles. The intermittent kiln prototype consists of a prefabricated structure or masonry of reduced size in easy assembly. The firing chamber is constructed with refractory materials inside to be able to withstand the continuous thermal changes caused by ignition and cooling which constitute the main characteristics of the intermittent kiln. The firing chamber is easily accessible to the loading and unloading by a door header. In the chamber can be introduced a cart on which are loaded the ceramic pieces to be fired. The car is of simple extraction for sliding wheels. Some of the outside cover of the kiln carts can speed up the loading time and unloading of the material. The firing curve adjusted with a management can be adapted to different types of ceramic materials to be fire. The intermittent kiln is to be considered suitable for few quantity productions, but suitable for high-value products for its running characteristics. It is setting allows you to also uphold small production without major constraints. The tools to get firing are the same of the other kilns, but in size and much smaller quantities, it follows that installing a kiln has a lower cost than the tunnel furnace. To select materials based on the properties is indispensable for setting up the prototype of the kiln. In this selection, account is taken the furnace is a constructive together subjected to harsh working conditions and in great efforts for expansion, thermal stresses of the, corrosion of materials. The furnace also must be constructed to vanish outside the minimum heat. For evaluating the materials to be used for the prototype, they consider the various parts of a furnace, in particular combustion chamber, refractories, bricks, insulating materials, heat recuperators. All assessments carried out in this first phase allowed us to verify what are the most interesting materials for the ceiling and walls. This is essential to try to decrease to a minimum dispersing heat through the body of the kiln and the fuel consumption. The validation of the selected materials is carried out by using simulation software (SIMU-THERM), a heat transfer calculation software, developed for design the kiln. Due to the precise mathematical modelling of the heat transfer process, also it is right for all kinds of high temperature applications. These preliminary simulations have allowed us, in this stage, to verify the best of insulating material of the roof and walls, to reach the "best" that is an acceptable compromise between the wall thickness and the time, i.e. between the density of the materials used and the thermal conductivity of the same. The SIMU-THERM software also allows us to check the progress of the temperature, see figure 1, in the wall of the kiln (curve 2), and outside the steel walls (curve 4). We insert in the program the theoretical curve of firing and the thermal conductivity of the individual materials of the layers of the wall of the kiln.

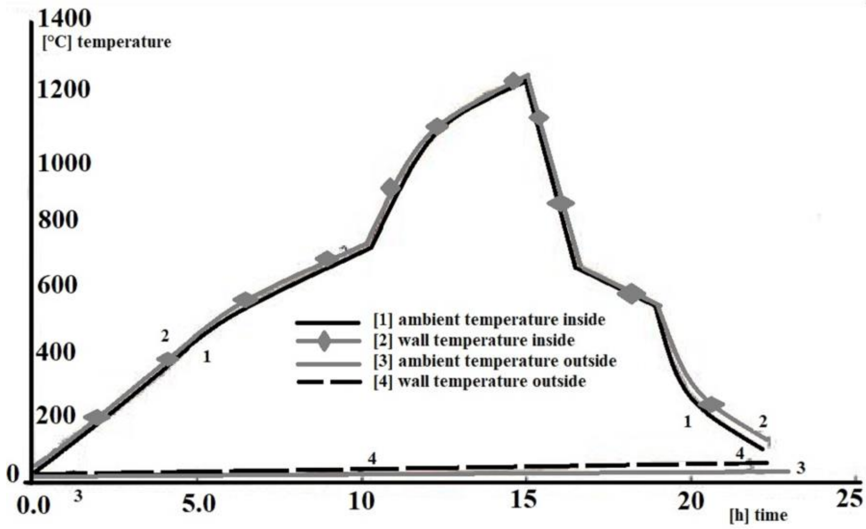

Figure 1. Graphic representation of the temperature behaviour inside and outside the kiln wall.

They are therefore performed a series of thermal simulations starting from the configuring a standard intermittent kiln, varying from time to time the materials and their thicknesses to check the values of the heat absorbed from the wall or from the time and the heat released by wall itself. This same software has allowed us to check the maximum temperature reached by the outer wall of the kiln.

2.2. Intermittent kiln construction

This paragraph described the assembly of carpentry, pipes and kiln insulation, following the indications received by the simulation software. This is particularly delicate because Economick shuttle kiln is a prototype and it is not possible to be sure of thermal dilatations and more in general its behaviour at firing temperature. Different processes are involved in this step. Firstly, it is important to ensure functioning the high-speed burners to distribute the heat evenly, thus the combustion process has been checked. Secondly, to guarantee an effective insulation, both vaults and walls have been designed to minimise heat loss toward outside. Thirdly, great attention has been given to the opening valves of the chimneys since those valves have a crucial role in ensuring the homogeneity in firing as well as allowing the leak of the hot fumes during the cooling phase. The electric board is installed. The control panel, which controls the pilot kiln, is mounted near the panel with the supervisory system (software with PLC) allowing precise metering of solid fuel into multiple locations in each of the kiln's combustion zones, with adjustable offsets for each delivery position as to keep overall energy uniformity. A Personal Computer, running the Microsoft Windows® operating system with expansion boards providing additional serial ports, host the software program for the intermittent kiln. Process interface signal acquisition electronics capable of stand-alone operation, coupled to the host computer via multidrop serial communications, and are installed. A set of loop controllers with a built-in communications capability has been set, to have a greater control over burner zones and pressure. The PLC software on the Personal Computer is tested. This is fundamental to allow the greatest functionality and efficiency of Economick kiln, as well as the related safety. Also is checked the alarms functioning and simulated some dangerous situations like over-firing, reduction conditions and others. It is worth mentioning that during this task, the software has been truly adapted to the needs to reduce any possible error. After the assembling and construction phase a trial protocol covering all the operations is performed, to run several tests to verify the functionality of each single component, in compliance with the requirements set in the applicable Machinery Directive. The tests are carried out through the simulation of its responses to real running conditions or emergencies. This task has been important to find out the best position of probes, sensors and thermocouples. After this we trialled different firing curves with the goal to find the shortest possible cycle though avoiding kiln lining damages. The instrumentation used to measure the thermal parameters of the shuttle kiln were some S-type thermocouples were arranged at the observation holes on the side walls to record gas temperatures at different locations. The temperatures of kiln brickworks are monitored by some S-type (platinum rhodium–platinum) thermocouples embedded in the refractory of kiln front door. A number of K-type (nickel chromium–nickel silicon) thermocouples are placed at the venting exits, venting tunnels, venting manifolds, entrance of chimney, and inlet/outlet of air preheater, to continuously record temperatures of flue gases at different locations and air temperature. At the venting tunnel and venting exits, a flue gas analyzer was used to sample at a flexible interval. A pitot tube is installed onto the exit of the air preheater to measure the dynamic pressure of airflow. The mass flow rate of air delivered is then calculated from the temperature and dynamic pressure measured. In addition, the temperatures of kiln walls, various pipes' surface, and ground surface in the neighbourhood of tunnels are monitored by contact thermometer, radiation thermometer, and thermal imaging system. During process heating period, the working staff manually adjusted gas flow rate according to experience to satisfy specific requirements. After every adjustment, gas flow rate, airflow rate, and flue gas part at the venting exits and venting tunnel are measured immediately. During operation time when there was adjustment of gas flow rate, flue analysis was checked two times in the production period and the wall temperatures and thermal imaging system were checked every 4 h.

2.3. Sanitary ware and tableware production test

We verify and optimize kiln's technological parameters and the safety of the system. An evaluation of kiln energetic performance and emissions is performed during the production phase. At the end we control the quality of products. Those activities allowed to off-set performance against the state-of-the-art intermittent kilns used as standard and available on the market.

3. Results and discussions

3.1. SIMU-THERM simulations

As described in subsection 2.1, the use of SIMU-THERM software has allowed us to verify the various conformations of the kiln walls. The cycles considered are those of the sanitaryware firing (22 h), normally used in production. By varying the insulation, it was possible to check how the stratification of the walls affects the heat released on the surface and simultaneously the absorbed heat. Table 1 shows some of the most significant tests insert in thermal simulation software, modifying the thicknesses of the innovative materials chosen for constructing the prototype. Tests 1-8, reported in table 1, are our possible solutions with the innovative materials, while test 9 agree to the Standard kiln used for comparison. Standard kill used different materials for the combustion chamber, and has a total thickness smaller than the simulations.

Table 1. Tests insert in thermal simulation software SIMU-THERM, modifying from time to time the innovative materials thicknesses chosen for the construction of the prototype. In tests 1-8 are change the thickness of the materials, while test 9 is the Standard kiln with different materials used for combustion chamber.

Test	Inside-1 Refractary fiber panel	2 Ceramic fiber	3 Refractary fiber panel	4 Ceramic fiber	5 Rock wool	6 –outside Steel	Total thickness (mm)
1	25	75	25	0	250	5	380
2	25	75	50	0	225	5	380
3	25	75	25	50	200	5	380
4	25	75	25	95	105	5	330
5	25	50	25	50	200	5	355

6	10	75	15	50	200	5	355
7	25	75	15	50	200	5	370
8	10	75	25	50	200	5	365
Test	Inside- 1 Cordierite Slab	2 Ceramic fiber	3 Verniculite panel	4 air gap	5 /	6 –outside Steel	Total thickness (mm)
9	10	210	40	60	/	5	325

The SIMU-THERM software allows getting a series of limits that we have reported in table 2, which allow us to identify the ideal solution for choosing the thickness of the materials used.

Table 2. Data obtained in different tests insert in thermal simulation software SIMU-THERM.

Test	Max outside temperature (°C)	Heat absorption inside (MJ)	Heat release outside (MJ)	Total heat balance inside (MJ)	Total thickness (mm)
1	54.8	37.56	14.69	22.87	380
2	46.2	36.90	15.89	21.01	380
3	53.1	37.42	14.82	22.60	380
4	49.5	37.39	15.06	22.33	330
5	55.8	35.90	13.68	22.22	355
6	62.6	35.60	12.04	23.56	355
7	58.5	38.23	14.17	24.06	370
8	55.2	34.44	12.62	21.82	365
9	90.9	62.26	28.86	33.40	325

As we can see in tables 1 and 2 we reported are important differences between standard shuttle kiln (test 9) and other simulation. First, we can note that the max temperature is very high (90.9 °C) instead, in the others simulation the max value varies between 46.2-62.6 °C. This behaviour is easily explained by the different quality of the walls: indeed, we introduced a material with very low thermal conductivity. As we can see important differences also in the heat absorption inside: this latter is the thermal energy required to realize firing cycle. To summarize higher values, mean higher methane consumptions. Obviously, this result is 2 aliquots: heat released at the outside and stored heat in the insulations. For this reason, the choice of materials used on a shuttle kiln must therefore always be the result of a compromise: on the one hand, the need to increase insulation, on the other the need to avoid an excessive increase in the kiln's mass. A shuttle kiln with an excessively heavy lining would require many heat to reach the high temperatures typically used for firing ceramic materials. In our simulation, we can see that standard shuttle kiln has a high-energy consumption (62.26 MJ) because there is an important heat store and release. As already wrote the release depends by insulation quality while stored heat depends by insulation mass. In particular, cordierite slab increases the final weight due to its high density (2000 Kg/m^3). To resume, all innovative simulations are an important improvement respect to the standard because increase thermal insulation and low total wall weight. From a more detailed analysis we note the best solution is insulation 2 because it's the best compromise between outside surface temperature (46.2 °C) and energy consumption (36.90 MJ). Furthermore, this is also the best constructive solution because it reduces total amount of ceramic fibre. This latter is indeed more difficult to assemble. It is also important to underline that solution 2 permits to reduce firing time (only 12 h) respect standard shuttle kiln. Indeed, thank to lighter insulation, it is possible to accelerate heating and cooling phase like in a tunnel kiln for sanitaryware and tableware.

3.2. Thermal control of the prototype and recovery results

First, the kiln atmosphere was controlled by determining the temperature of the wall and by measuring the real oxygen content in the combustion chamber (to preserve product quality and optimise the combustion process) [7]. In figure 2 we reported the thermal images, or thermograms, are actually visual displays of for infrared energy emitted, transmitted, and reflected by ECONOMICK kiln [8]. The thermal imaging camera (instrument used for analysis model Testo 882) is employed for obtained a series of pictures for both the kilns. This functionality makes the thermal imaging camera an excellent tool for preserving electrical and mechanical systems in ceramic industry. By using the proper camera settings and by being careful when capturing the image, electrical systems and combustion camera are scanned and problems can be found. Faults with steam traps in steam heating systems are easy to locate. In the energy savings area, the thermal imaging camera can do more. Because it can see the effective radiation temperature of an object as well as what that object is radiating towards, it can help locate sources of thermal leaks and overheated regions as well.

Figure 2. Thermograms obtained in ECONOMICK and standard kiln.

In particular, for a comparison of kilns, since they are complex systems, it is essential to understand the punctual measurement of temperature with thermocouples, and / or pyrometers, is not enough for a correct and complete analysis. The many problems that can be encountered depend on different causes that often act in parallel on large areas and so it is necessary to be able to simultaneously analyse sections as wide as the system. Therefore, thermocouples fixed on specific points, fundamental for the continuous control of the estimated temperature of the product, offer little relevant information on the specific problems that can arise in different parts of the kiln.

As can be seen from figure 2, the ECONOMICK kiln shown less heat dispersion (especially through the door), with consequent homogeneity in the combustion chamber. The use of insulating materials with better thermal performance thus gets a ceramic product with uniform firing in all its parts.

A detailed study is then performed of the combustion in the burners to control the excess air coefficient in the burners by O_2 probe and by methane consumption. The data obtained are then used to estimate the recovery energy during the combustion. Thanks to O_2 probe, ECONOMICK kiln further reduced gas and electric energy consumption with 90 kcal/kg and 24 KWh, respectively.

During production, the thermocouple checked firing homogeneity and using refractory cones and rings we have the control. In ECONOMICK there are no temperature differences between different kiln zones. To have an idea, the maximum gap in conventional kilns can go up to 25°C. So higher sanitaryware thickness (up to 20 mm) are normally requested to avoid mechanical cracks. Due to this full homogeneity in production it was possible to lower thickness with 10% and so to save raw materials. Quality assessment is ascertained there was no difference in the qualitative standards of the pieces produced with the ECONOMICK kiln for pieces produced in its conventional shuttle kiln. 3.360 sanitaryware pieces are produced, 3.225 were of first quality, implying a 4% of scrap, according to the expectations.

The results with the ECONOMICK kiln in sanitaryware production are reported in table 3 below:

Table 3. Results obtained from the data registered during sanitaryware production.

Characteristic	Standard kiln	Economick kiln
Methane (Nm^3/ kg of fired piece)	0.29	0.15
Thermal Energy consumption (kcal/ kg of fired piece)	2630	$1395^a/1305^b$
Raw material consumption (%)	/	- 8-10%
CO_2 (g/ kg of fired piece)	0.58	0.30
Tmax combustion air (°C)	/	> 350
Cold wall temperature (°C)	>50	< 50
Firing cycle (hours)	22	12

[a] measure obtained without O_2 probe. [b] measure held with O_2 probe

About percentage reductions, (for example Nm^3 of Methane, CO_2), it's important to underline that are referred to standard shuttle kiln that consumes slightly more than standard (2630 kcal/kg instead 2400). The reason is the higher T_{max} temperature of sanitaryware production (about 1280°C). Anyway it's important to observe:

- Final ECONOMICK Thermal energy consumptions are only 1305 kcal/kg instead 2630 of standard kiln. This explains why final emissions saved are -47%
- Coel burners confirm their efficiency in the secondary NOx decrease (-54%).
- The software change and probe introduction improved combustion efficiency and kiln flexibility because is now possible to check and select internal atmosphere.
- Economick shuttle kiln confirms thermal simulation: thanks to its insulation is possible to have shorter firing cycles (12:00 h) and < 50 °C cold wall temperatures.
- It's been possible to reduce 8-10% sanitaryware thickness thanks to better firing homogeneity inside the kiln.
- Air combustion is preheated up to 400°C.

The ECONOMICK kiln is used for production of 30.800 tableware pieces produced saving -50% methane consumption and thus – 50% CO_2 emissions, and reducing NOx emissions with -54%. As shown tableware, results are reported in table 4.

Table 4. Results obtained from the data registered during tableware production.

Characteristic	**Standard kiln**	**Economick kiln**
Methane (Nm^3/kg of fired piece)	0.64	0.32
Thermal Energy consumption (kcal/kg of fired piece)	6005	3010[b]
Raw material consumption (%)	/	- (8-10)
CO_2 (g/ kg of fired piece)	1.28	0.64
T_{max} combustion air (°C)	/	> 350
Cold wall temperature (°C)	>50	< 50
Firing cycle (hours)	12	12

[a] measure obtained without O_2 probe. [b] measure obtained with O_2 probe

The most important achievements are summarized as follows:

- Final ECONOMICK Thermal energy consumption is only 3010 Kcal/kg instead of the 6005 Kcal/kg of a conventional shuttle kiln.
- Coel burners confirm their efficiency in the NOx reduction.
- ECONOMICK software perfectly adapts to the Tableware firing cycle.
- It has been possible to reduce thickness with 2.5% thanks to better firing homogeneity inside the kiln.
- Air combustion is preheated up to 300°C.

4. Conclusions

The thermal efficiency of this prototype is in line with that of a continuous furnace, through the recovery of sensible heat of the flue gas used for preheating the combustion air. In addition, the latest generation of insulating allows to greatly reducing the heat losses of the furnace. Finally, an optimized control system of the air / gas ratio allows you to preserve a higher efficiency. All this is realized in ECONOMICK project. Thanks to a computerized management of air and gas flow, the almost complete reuse of warm air from cooling and advanced materials for thermal insulation, the Results are 3360 sanitaryware and 30800 tableware pieces produced saving 47% and 54% methane consumptions respect standard shuttle kiln respectively. This meant to reduce emissions of CO_2, SOx, NOx, dust and HF. About NOx we got saving of -54% thank to a better check of air /gas ratio flow rate. However, thanks to ECONOMICK lining low thermal inertia is possible to have a short firing cycle in sanitaryware production (12 h) improving flexibility. The production concerned the traditional ceramic bodies for sanitaryware and tableware, which are compared with items fired in a standard intermittent kiln, functioning in parallel with the same procedures. By substituting traditional tunnel kilns with ECONOMICK kiln, European industries - in particular SMEs – can drastically reduce their costs for production.

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