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Experimental Study and Energy Optimization of a Prototype Furnace for the Pottery-Ceramic Industry

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ABSTRACT

In the current context of global warming linked to a significant consumption of energy and the emission of considerable amounts of greenhouse gases, it is imperative to optimize the thermal operation of industrial furnaces to reduce consumption and protect our environment. The article focuses on the heat treatment of pottery-ceramic products in a prototype furnace to improve energy efficiency. And thus, the fuel consumption and the corresponding carbon dioxide emissions. In order to make a judicious choice of the best indicator that characterizes the energy efficiency (efficiency and power) and after simplifying the firing process we precede to a parametric identification; this was being done from the measurements made on the process. We propose a prototype gas furnace and we are doing a comparative study of randomly charging and with supports for the firing of ceramic products whose objective is the determination of the optimal operating conditions with respect to an energy criterion taking into account the quality of the product. In this work an experimental analysis with a specific energy consumption (SEC) of 1.15-1.38 kJ/kg prototype furnace is presented and compared to the experimental tests carried out at the traditional furnace of 6.75 kJ/kg used in the pottery-ceramic industry in Morocco. The results of this study show that for firing using supports canals leads to a product of good quality and with reduced consumption between four to six times less of that used by the traditional furnace. On the other hand, the finding of the study show that the prototype furnace emits 402.48 $kgCO_2eq$ less compared to traditional furnace ($5875kgCO_2eq$) which allow us to reduce the harmful emissions.

1. Introduction

Energy is one of the key factors to the development of a nation. Since the world is witnessing an industrial and technological revolution, it has become essential to consume much more energy in order to achieve some technological advances. However, this contribution has its drawbacks that

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need to be taken into consideration. Since the energy sources in the world are limited saving energy is a challenge in modern life [1]. Some of the encountered problems that fossil fuels may cause to the planet earth are pollution and global warming which makes it necessary to reduce the energy utilization as well as to think of energy alternatives [2,3]. Environmental issues are mainly caused by fossil fuels due to the emission of greenhouse gases that lead to climate change [4]. Global temperature has also risen by approximately 0.74% over the last 100 years and is expected to rise by 6.4% by the end of the century [5].

As it is probable that the high energy cost is yet to continue, it has become obligatory that we make much more efforts to utilize energy in industry and buildings effectively. Generally, energy utilized in all kinds of structures has rapidly come into attention as there are basic hardships to meet the changes that happen to the environment. Positively no other industrial sector has more concern on energy use and related ozone harmful emissions. Other industries don't have this type of harmful emissions that has to be reduced through energy proficiency improvement. Statistical data demonstrate that structures consume up to 40 % of the entire global energy and account for 33% of global greenhouse gas emissions. By the end of 2030, the energy utilization is predicted to rise up to 50 % [6,7].

Nowadays, it is accepted that among the greenhouse gases, CO_2 is the most harmful greenhouse gas that is caused by fossil fuels, carbon dioxide accounting for 80% of the impact [8]. And CO_2 has caused several damages such as global warming over recent years. Moreover, nonrenewable resources, such as fossil fuels, made up of natural gas, coal, and oil, are higher in demand and have recorded being dwindles gradually [9]. Energy management and renewable energy have now been increased all over the world via various motivations [10]. As a consequence, CFD methods provide tools to optimize the fuel consumption and provide a better control of the harmful effects on the environment [11].

Heat transfer improvement is any process objectives to enhance the performance of a heat system or to increase heat transfer coefficient, which has been a challenge for the researchers to find and figure out the optimum heat transfer in order to get optimum outcomes for the industries [12] through utilization of various techniques. Heat transfer improvement grows significantly in recent years as it contributes in reducing the use of the fossil fuel which lead to a reduction in emissions of carbon-dioxide and the effect of greenhouse reduced [13,14].

Apart from conventional methods to increase heat transfer inside industrial cavities and in duct such as fins and extended surfaces, the use of a porous medium has also become an interesting method to increase heat transfer in recent years [15]. In addition to that, heat transfer rate is improved when the vertical length of the heating element is greater than the horizontal length [16].

In the energy sector in Morocco, energy is one of the key factors of development. Due to its demographic growth and its needs for economic and social development, Morocco is generating a growing demand for energy. However, it faces an energy constraint due to its strong dependence on the outside world and the massive use of traditional energies including biomass [17].

On the economic front, ceramics is one of the sectors that is experiencing significant growth in the national economy. The refractory products industry is the most common in northern Morocco. Natural clay materials are abundant in this region. They play an important economic role with a national production of about 45% for refractory materials. However, the national production of ceramics is still insufficient, and to fill this deficit the Moroccan government must import ceramic products from overseas [18,19].

Nevertheless, the predominance of the use of traditional furnaces may hinder its development, due to the demands of the international market in terms of product quality and respect for the environment. The firing systems used by the ceramics sector in Morocco are still 95% traditional according to the Ministry of Industry in Morocco. This finding clearly establishes the cause-and-effect relationship between this energy practice in ceramic products and the deforestation phenomenon (18 Hectar per year) and the use of plastic waste [17]. The low level of efficiency recorded, means that huge losses of energy are recorded at these furnaces.

The production of refractory materials by ancient ceramists remains the main challenge for manufacturers. The re-production of pottery-ceramics involves determining, on the one hand, what raw materials were used and how they were prepared and, on the other hand, how the products were formed, decorated and fired. The main purpose of technological studies is to determine the firing temperatures of pottery, their mechanical and thermal properties [20].

The thermal and mechanical behavior of the clay-based material is strongly influenced by the microstructure of the product. A thorough characterization of the microstructure of refractory materials is necessary in order to establish micromechanical models, which make it possible to derive macroscopic physical properties on the basis [21].

The ceramic industry is well known to be characterized by energy intense processes [22]. In particular, the furnace for the firing of the ceramic product is the main process that employs a large amount of energy [23]. High temperature furnaces operating in the range of 900-1500°C are widely used in these sectors for this purpose. Recent regulations for the energy consumption require a more accurate design of the furnace in order to limit the fuel. Furthermore, the environmental concerns drive the design towards cleaner systems and more stringent limits about the pollutant emissions [24].

This study will cover a critical research gap that arises because empirical studies are no longer sufficient to lead to innovative and competitive products; in addition, to the lack of research works in this field. Thereby; efforts to convert traditional furnaces into gas furnaces remain limited and given the high cost of gas furnaces that exist on the market. This work sheds light on the importance of producing local furnaces at reduced cost and also to do work incentive argumentation to convince craftsmen to equip themselves with a gas furnace which will not only have a positive impact on the environment but also the quality of the product.

Faced with this situation, it seems urgent to propose alternative solutions to the current methods and means of firing which are the main basic elements in the clay-based products industry, which will make it possible to better envisage a real sustainable development [25].

During firing, the theory of heat transfer has been utilized mostly in the industrial and engineering sector. Heat transfer is the mechanism of the movement of energy with regards to the temperature difference and it is to a temperature gradient. Heat transfer process may involve conduction, convection or radiation [26].

The current economic and environmental context, dominated by the energy crisis and global warming, makes it necessary to optimize the operation of thermal furnaces by controlling performance, which is the way of charging and power. The objective of heat treatment in high temperature furnaces, respecting the firing protocol, is to improve the mechanical properties of materials, such as toughness, hardness and corrosion resistance. Due to the continuous development of technology, demand for heat treatment increases, especially the precision and temperature uniformity inside the product [27].

Different approaches have been adopted for the optimization of the furnace performance. In particular, a theoretical formulation for the prediction of the furnace operating characteristics has been proposed [28]. In a numerical model has been proposed and implemented into a Fortran language for evaluating the temperature distribution within the walls, gas and product along the furnace (Figure 1 and Figure 2) [29]. A numerical simulation on the variation of the vacuum rate parameter (Figure 9) and burnt gas flows (Figure 10) has already been used to optimize the energy consumption of the entire prototype furnace [30-32].

The research project that is the subject of this study, focuses in particular on the substitution of traditional polluting furnaces in clean, economical and secure gas furnaces for firing clay-based objects, the purpose of which is to determine a firing protocol for each type of product on the one hand and on the other hand to reduce energy consumption and protect the environment.

2. Methodology

To achieve the previously mentioned objectives, our study is based on the access to an improved gas furnace using butane gas as an energy source. To obtain experimental data, a prototype was installed at the Akrach site (Rabat). We have completed ten firing trials on the newly realized experimental device. The firing tests carried out on the new prototype will be able to inform us about

i. The appropriate firing methodology for each type of product.
ii. The energy efficiency of the prototype furnace.
iii. The socio-economic and environmental impact of this technology.

Also, these tests will allow us to carry out a quantitative and qualitative comparison with the traditional system and this, on the basis of the tests carried out on the latter and the data available in the literature or collected from the potters of the Akrach site.

The firing tests carried out on the prototype furnace consist of

i. A follow-up of the evolution of the temperature according to time and according to the gas outlet pressure, and this by sampling at each time
   - The temperatures inside the furnace and at the level of the chimney using thermocouples linked to data loggers.
   - The pressure of the butane gas by a manometer fixed to the outlet of the furnace in question.
ii. Determination of the quantity of gas consumed during each test.
iii. Determination of the total mass of fired pieces and the quantity of underfired, deformed or broken pieces.

This will then allow us to calculate

i. The specific consumption of the furnace (kg of fuel per kg of pieces).
ii. The average thermal power of the prototype furnace.

3. System Description

3.1 Experimental Equipment

To reach the goals mentioned previously, our study is based on the design and installation a prototype furnace using the butane gas as fuel in site Akrach- Rabat.

The experimental design is constituted by a surrounding wall of parallelepiped shape and by capacity 4.6 m^3. This prototype is built in masonry with local materials (bricks, refractory plates, chamotte, glass wool, etc.). The system of insulation was assured by the ceramic fiber and the glass wool at the level of the furnace and at the level of the door.

This furnace is characterized by the presence of a firebox. The gas supply is guaranteed by cylinders of butane gas placed outside of the room (condition of safety). This gas is brought up to the atmospheric burners by means of two conducts placed on each side by the furnace. This technique was chosen to allow an adequate and fast transfer of heat. Every burner contains its own gate of safety which closes the gas in the case of an extinction of the flame. A manometer placed in the upstream allows making sure that the gas is for the suitable.

Firing indicators or thermocouples should be used in order to better control the firing. These instruments can be introduced through openings placed at the top of the furnace (chimney).

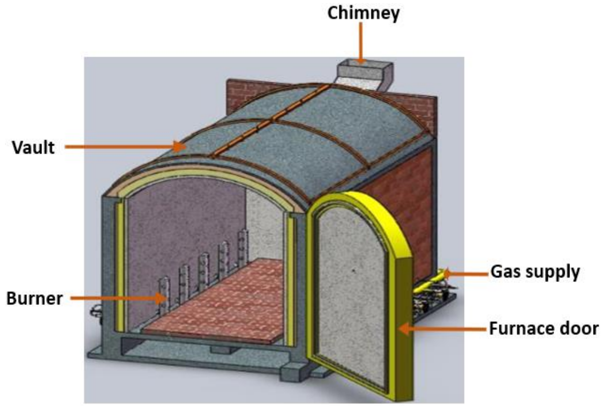

Fig. 1. Prototype furnace designed

Fig. 2. Prototype of improved gas furnace made

4. Experimental Results

Before starting the firing of ceramic materials, we therefore cleaned the burners which made it possible to have correct flames and the firing test was launched by installing Chromel-Alumel type thermocouples connected to dataloggers in order to record the temperature evolution in the prototype furnace.

4.1 Blank Firing Tests

Before the realization of the first firing tests, it was preceded first of all to tries in empty furnace to stabilize materials. The test lasted approximately ten hours, the maximum temperature reached was of the order of 900°C and the rise in temperature was 140 °C/h.

The three temperatures at the door (level 0, center and top) are the same indicating that there is no vertical temperature gradient (Figure 3).

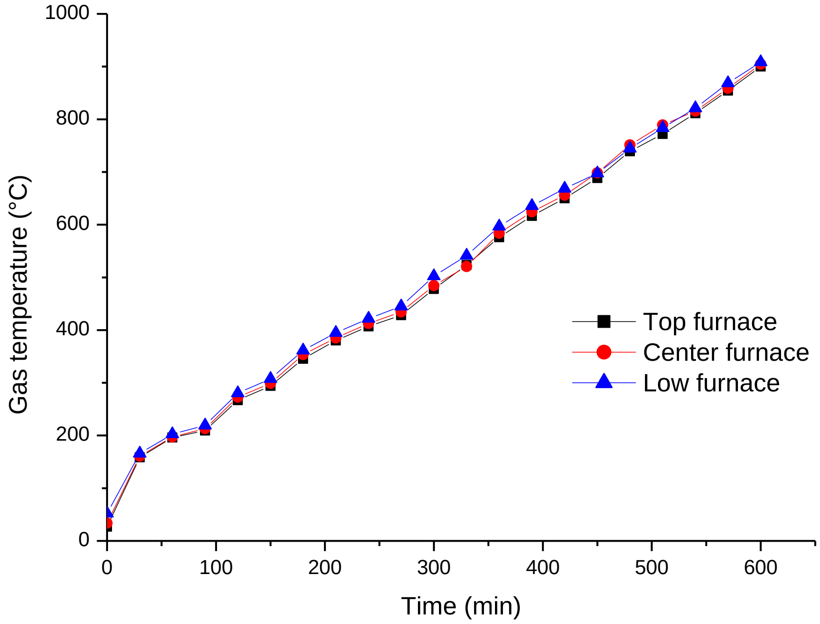

Fig. 3. Vertical temperature profile vacuum firing

4.2 Low Load Firing

A firing test with a reduced load (Figure 4) was started to control the temperature rise and check the firing quality.

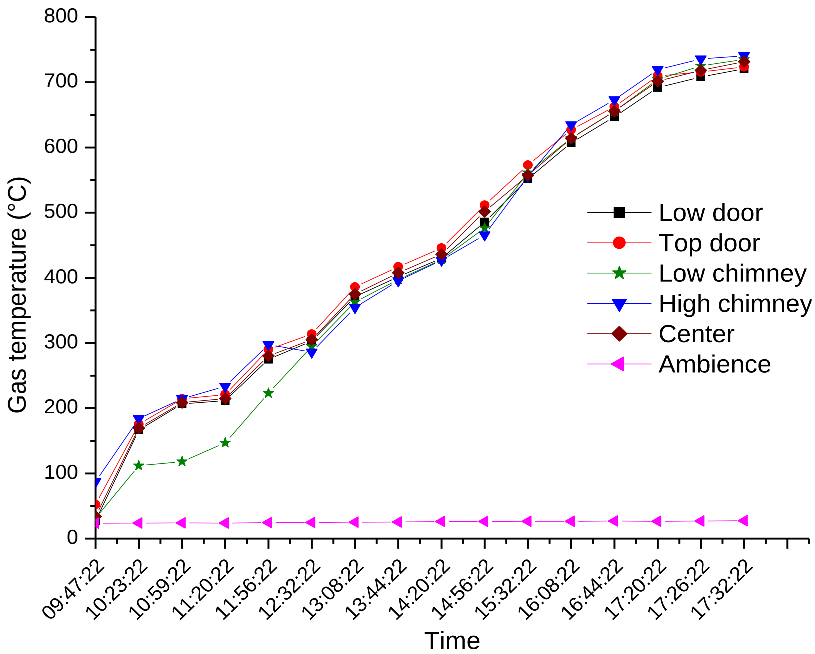

Fig. 4. Temperature profile with a reduced load

The firing of the pottery pieces lasted eight hours, the maximum temperature reached is of the order of 800 °C.

The recorded temperature profiles indicate that the temperature is homogeneous inside the furnace. The temperature at the low chimney adjusts with other temperatures once the damper is closed.

The tests allowed the firing of different types of products according to quality standards in the field of ceramics.

4.3 Firing Test with Full Load

A firing test with a 100% filler was carried out (bulk loading in the usual manner of potters) of ceramic product. The furnace was loaded according to the traditional potter's method (Figure 5). No supports were used and firing was of the single-firing type.

Fig. 5. Full load firing

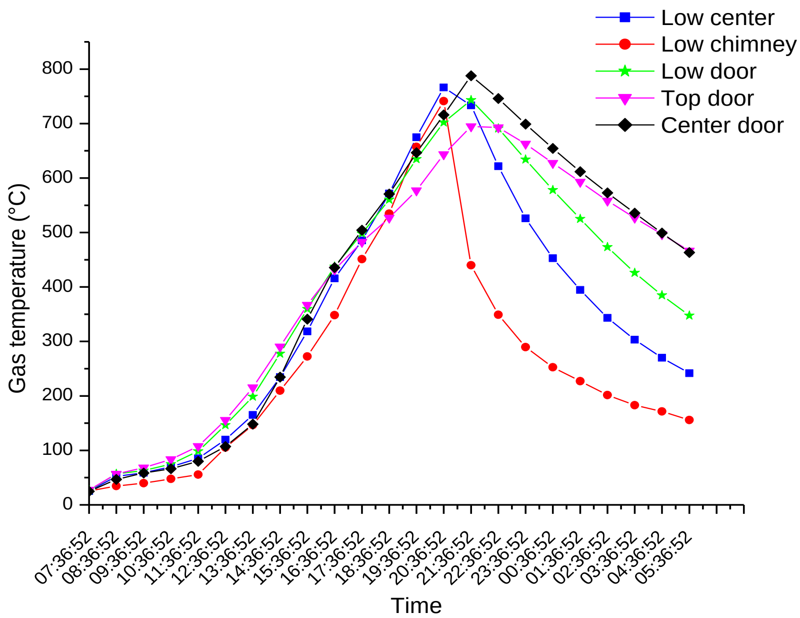

Fig. 6. Temperature profile with a with a 100% filler

The temperature records show that the furnace is fairly homogeneous. A difference of 45 °C is recorded between the top and bottom of the furnace. The temperature at the low chimney has a difference of 90 °C with the top of the furnace but once the damper was closed at 17h15 this temperature aligned with the others while the door temperature (high level) has decreased by 60 °C compared to others.

The quality of the firing was average. The charging method of the furnace caused some products to be installed just above the burners, these products were partially burned. Loading for this type of should be done with adequate supports. The loading mode is essential and the use of supports has been decided. In addition, a laboratory firing test would make it possible to set the appropriate firing temperature for Akrach clay.

In the case of bulk loading, the furnace was too full and suffocated and the heat could not reach the upper half of the furnace. The trial was therefore deemed inconclusive. In addition, firing requires more time and therefore more energy. The consumption in this case is of the order of 1.38MJ per kg of pieces.

4.4 Baking Test with Supports

Another test using the supports was made with ceramics. The charging was done in such a way as to leave space between the burners and the product (Figure 7) to avoid the destruction of ceramics placed above the burners. The products to be fired are placed with spacing between them so as to favor the best circulation and transmission of the heat [30].

Fig. 7. Firing with supports

Table 1
Firing results at furnace level using supports

Time (s)	Top door	Low door	Center door	Ambience	Top chimney
0	20,6	19,8	20,2	18,7	33,4
3600	130,1	63,9	71,7	19,8	107,5
7200	165	87,3	101,9	19,4	147,7
10800	197	118	151,4	21	181,6
14400	248,2	160,7	205,9	20,9	220,3
18000	307,5	216,4	290,8	20,2	278,4
21600	388,9	290,7	374,8	19,1	389,9
25200	484,3	379,2	491,7	19,8	522,2
28800	569,9	487	597,6	19,5	623,8
32400	650,8	565,8	691,1	19,3	700,8
36000	732,3	677,6	779,3	18,8	771
39600	809,3	768,5	858,9	20,2	839,8
43200	834,2	805,3	833,4	22,1	836
46800	779,4	730,5	764,7	22,6	767,1
50400	717	659	697,4	22,5	702,5
54000	659,9	595,8	637,2	21,7	646,4
57600	608,8	539,8	583,8	21,6	597
61200	563,9	484,4	536,6	21,2	554,2
64800	522,5	435,4	492,1	20,2	514,5
68400	483,5	389,9	450,4	20,3	476,7
72000	446,8	348,9	414	20	441,4

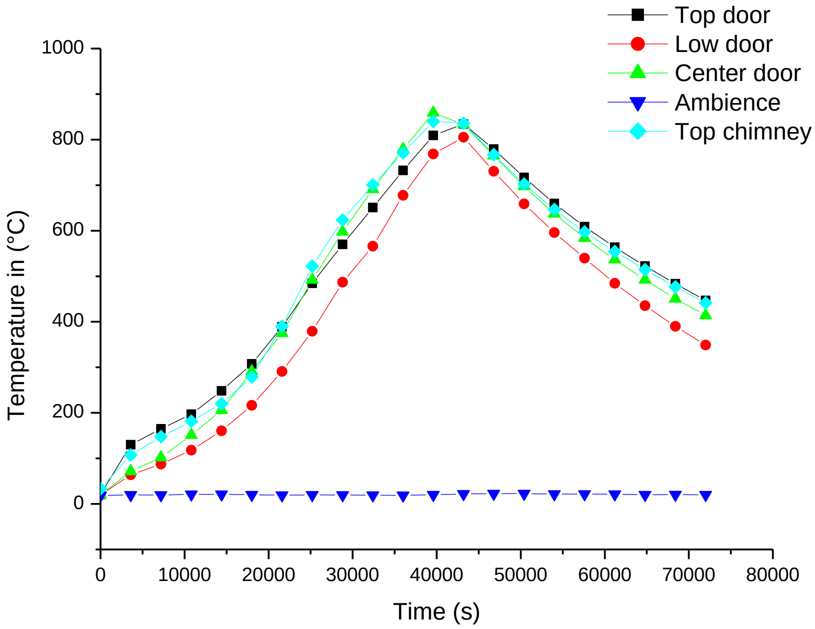

Fig. 8. Temperature profile with supports

The firing quality was very satisfactory. The ceramics were well fired and flawless. The fall rate was 5% (the falls are cracked products probably due to the drying which was not sufficient at the time of the test which took place in March).

The charging mode is very detrimental to the quality of the firing: Pricing must be uniform so as not to create preferential routes to the inside the furnace. Indeed, in an atmospheric furnace, the draft is natural and a heterogeneous charge causes preferential paths leading to products of disparate and variable quality. The firing of the products is perfect with the aforementioned temperature. The standards provide for a firing temperature range between 950°C and 1050°C for this product. In addition, the energy consumption in this case will decrease, it is of the order of 1.15MJ per kg of pieces instead of 1.38MJ per kg of pieces in the case of bulk charging and 6.75MJ per kg of pieces in the case of a traditional furnace.

According to the results of firing in the prototype furnace, we observe that when empty we obtain the temperature of 800°C after 8 hours of furnace function. When the furnace is loaded, the evolution of temperatures is slow, the temperature 800 °C is obtained in 11 hours of function of the furnace with supports and 14 hours of function without supports. The use of supports is mandatory to optimize energy consumption.

5. Test Simulation

Figure 9 and Figure 10, respectively show the evolution of firing temperatures according to the filling rate of the product and according to the mass flow rates of the gas according to Balli and Touzani [29].

From Figure 9 and Figure 10, it can be seen that the rate of rise in temperature, the maximum firing temperature and duration maintaining it depends essentially burnt gas flows (thermal power) and vacuum rate.

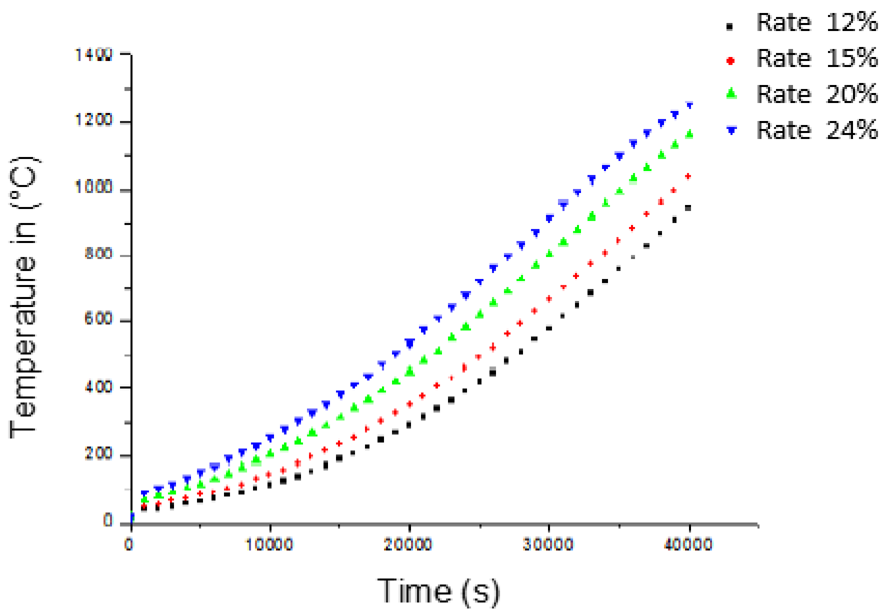

Fig. 9. Evolution of the temperature according to the filling rate

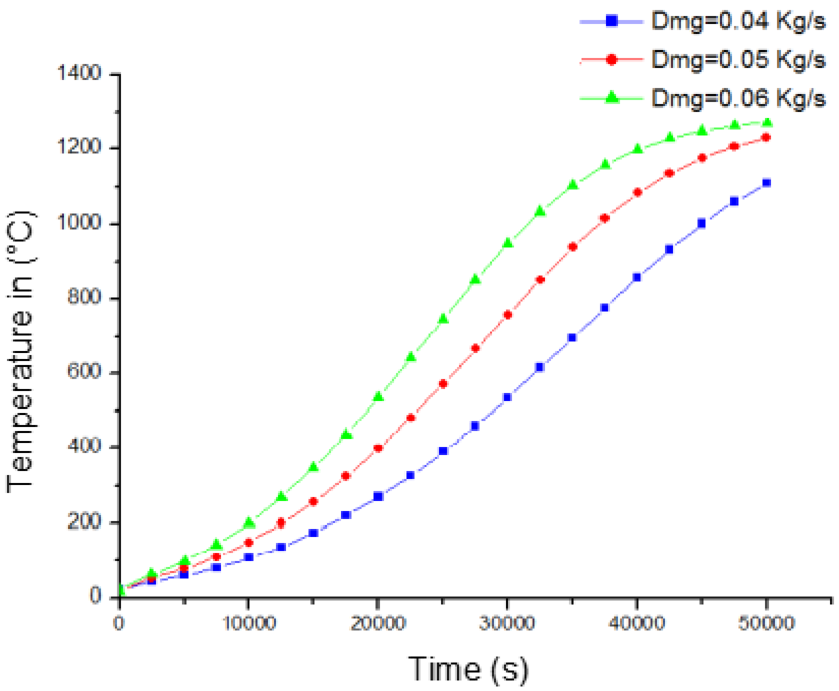

Fig. 10. Evolution of the temperature according to the mass flow of the gas

6. Comparison of Test Results for Different Types of Furnaces

Table 2 shows the different results obtained for different types of furnaces used (Traditional Furnace (T.F) and prototype of improved furnace (P.F)) in the production of ceramic products.

Table 2
Firing results for different types of furnaces

Type of furnace	Traditional furnace (TF)	Prototype furnace (PF)	
		In bulk	With supports
Firing time (h)	12	14	11
Type of combustible	Wood	Gas	Gas
Quantity of fired pieces (Kg)	8000	4000	4000
Firing cost (Dh)	1500	420	350
Firing cost /kg of pieces	0.19	0.105	0.087
Energy supplied (MJ/kg of pieces)	6.75	1.38	1.15
Average power (kW)	1250	109	116

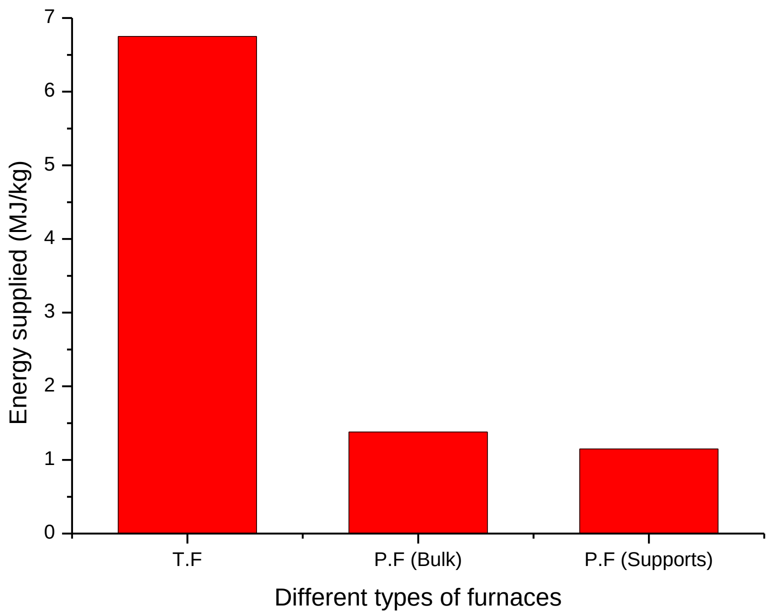

Fig. 11. Energy supplied for different types of furnaces

It can be seen that firing at the traditional furnace requires amounts of energy 4 to 6 times higher than those used in improved gas furnaces (Figure 11). This is mainly due to the reduction of thermal losses at the latter. It can be concluded from the tests carried out on the new prototype that the firing of the product has been satisfactory and the new furnace has the following advantages

i. Good homogeneity of the temperature inside the furnace if a homogeneous charging is respected.
ii. A relatively good consumption: 9 to 10 cylinders of butane are sufficient for firing or costs about 350 Dhs per firing.
iii. Gas furnace investment costs are a major factor in the decision to involve ceramists in the project to replace traditional furnaces with gas furnaces; more efficient and economical with affordable prices and equipped with security systems.

7. Conclusions

Even the energy situation of ceramics using inefficient equipment could be improved by the adoption of more efficient equipment, or better alternative fuels to wood (butane gas for example). However, the adoption of these high-performance equipment and alternative fuels is conditional on the elimination of various obstacles.

Following the tests carried out on the gas furnace, we can conclude that the prototype furnace has a high efficiency of an energy supplied of 1.15MJ per kg of parts in comparison with that of the traditional furnace which an energy supplied of 6.75MJ per kg of part. Indeed, the firing of the ceramic product requires a lot of precautions to know

i. The product must be sufficiently dried and preheated before firing.
ii. The way of heating is very detrimental to the quality of firing: The charging must be homogeneous so as not to create preferential paths (use of supports). Indeed, in an atmospheric furnace, the draft is natural and a heterogeneous charging causes preferential paths (the hot gases take the path where the pressure drop is low).

Heating should be done according to a pre-established firing scale (curve). The velocity of rise in temperature should not exceed 75 °C / hour while before reaching 250 °C.

The use of this technology allows us to have a correct energy consumption that will definitely have a positive impact on the environment.

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