Caspian Journal of Environmental Sciences
Online ISSN: 1735-3866
Print ISSN: 1735-3033

Environmental consequences of firing technologies evolution in ceramics

Gulnara Ildarovna Safina[1*], Olga Borisovna Ushakova[2], Firdania Damirovna Mubarakshina[3], Ildar Shavkatovich Safin[4]

1. Department of Design and National Arts, IFMK, Kazan Federal University, Kazan, Russia
2. Department of Architectural and Building Structures, SPbGASU, St. Petersburg State University of Architecture and Engineering, St. Petersburg, Russia
3. Department of Design and National Arts, IPMK, Kazan Federal University, Kazan, Russia
4. Department of Radiophotonics and Microwave Technologies, KNRTU-KAI, Kazan National Research Technical University, Kazan, Russia

**Corresponding Author's Email: gulnara89119824693@yandex.ru*

ABSTRACT
Technical ceramics are one of the numerous materials, including metals, glass, and plastics that can be utilized to preserve and protect the environment and also contribute to regenerate damaged ecosystems. This article examines the historical development of pottery, focusing mainly on the organization of the technological process of firing ceramic products as well as its environmental consequences. To obtain durable ceramic products, it was necessary to improve the design of the kiln and increase the firing temperature, which led to the appearance of specialized kilns. For a long time, firewood and coal were the fuels used for firing. Then, as humankind's mastery of the natural environment progressed, fuels in the form of liquid and gas were used in pottery kilns. Today, the advent of electric heating elements has made it possible to simplify the firing even further; the thermoregulation equipment of modern kilns allows potters to maintain a stable temperature throughout the firing process, leading to the increased quality of the final product. The results of this study will provide a complete picture of the various types of ceramic kilns found throughout history, considering relevant environmental issues. It will help to trace how the quality of ceramic products has been influenced by the design of the kilns and the increase in firing temperature while maintaining the damage to the environment to a minimum. This will be of interest both to professional and amateur potters, who may find it useful during the firing process.

Keywords: Ceramics, Ecosystems, Firing temperature, Kilns, Porcelain, Environmental consequences.

INTRODUCTION
Ancient ceramics date back to the time when mankind first discovered fire. More precisely, burnt shards of clay are the evidence of this use of fire by man. With the invention of fire, mankind was given the opportunity to create ceramic dishes, firing clay products on a bonfire. Fragments of ceramics found by archaeologists prove the existence of ceramics and the use of fire for its manufacture. The first clay products were primitive and fragile, and they were fired at low temperatures in ordinary bonfires. Over time, the manufacturing technologies of products, the technology of firing, and the design of kilns developed and improved. The development of technology and an increase in the firing temperature had a decisive influence on ceramics. Products became more durable, more complicated, and took more decorative forms. Later, before firing, the preforms were covered with enamels and glazes, which made the ceramic surface glossy and the products themselves more durable.

The impact of mineralogy, microstructure and terminating temperature on the viable warm conductivity of conventional hot preparing pottery was examined (Allegretta, I., Eramo, G., Pinto, D & Hein, A 2017). Most extreme terminating temperatures were resolved for an enormous and variable assortment of clay sherds from Bulgaria utilizing attractive helplessness estimations. The information acquired were joined with the current

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

archeological confirmations as a first endeavor to clarify the mechanical improvement of ceramics creation in four significant Bulgarian archeological destinations – Plovdiv, Pliska, Veliki Preslav and Dragovishtitsa (Kostadinova-Avramova *et al*. 2018). Rietveld refinement results indicated that LiF, CaF2, SrF2 and BaF2 earthenware production solidified into a cubic structure with space bunch Fm-3m (Song *et al.* 2019).

Conventional clay forming is the beginning stage and last objective of earthenware product creation. It is the intersection of a long cycle in the innovation advancement. It is imperceptible throughout the entire existence of artistic innovation development and in the creation of every clay item (Sun 2019). In different parts of the globe, kiln designs underwent their own particular, characteristic changes. For example, in Mesopotamia, two-chamber kilns in the form of a dome were built, which made it possible to stabilize the firing temperature and obtain products that were not covered with soot. A horizontal extension of the kilns in ancient China made it possible to raise the firing temperature and led to the invention of porcelain. The primary aim of this study was to investigate the history of the evolution of firing technologies in Ceramics and its environmental Consequences in order to contribute to figuring out how the quality of ceramic products can be affected by the design of the kilns and the rise in firing temperature, considering keeping the environmental damage to a minimum.

MATERIALS AND METHODS

To identify the main stages in the evolution of the designs and materials of pottery kilns, to determine the ways in which firing technologies improved, and to identify types of fuels for kilns and the features of increasing firing temperatures, the researches of historians and archaeologists, the experience of potters, technologists, artists, as well as literary sources were all studied. The studied materials were systematized, which allowed us to build a history of the transformation of firing technologies and describe the most exciting types of ceramic kilns.

RESULTS AND DISCUSSION

The first ceramic products were fired at a low temperature in the flame of an ordinary fire. But, with the development of the skills of the heated treatment of food, ancient people thought about creating cooking utensils. And plastic clay was well suited for this. In the primitive kitchen utensil that people learned to sculpt, it was possible to boil water or store food. The found ancient samples and fragments of dishes that people used belong to the Upper Paleolithic era (XVIII-XXI millennium BC). They were found in settlements in Africa and Asia (https://en.wikipedia.org). Later evidence was found on the territory of the Republic of Tatarstan; these are the findings of scientists in Bilyarsk (Pyataev *et al.* 2015) and Bulgar (Ivanova *et al.* 2017). They are shards of ceramics and fragments of vessels, indicating that not only local sources of raw materials were used in medieval craft centers. Using the methods of modern physics, it was revealed that the firing temperature of the products was less than 500°C; that is, our ancestors used single-chamber bonfire kilns.

In parallel with the development of ceramics, ancient people smelted metals and created metal tools; this also required special furnaces and kilns. For greaterconvenience in controlling fire, using fuel efficiently and reaching high temperatures, larger kilns began to be created, and their designs became more complicated. In different parts of the world, firing technologies developed at different speeds, but on average firing, temperatures increased by about 100°C per millennium. It all started with bonfires and pit firing in specially dug large pits, where it was possible to burn several tens or even hundreds of products at a time (Fig. 1). As a rule, it was not possible to get a temperature above 700-800 °C in such firing, but this was enough at first to increase the strength of ceramic products and reduce their porosity. These firing methods are used today in Africa and Latin America, where the use of early technologies has been preserved (http://www.ceramicstudies.me.uk).

Products fired at a low temperature were porous and absorbed a lot of moisture. As a result of these deficiencies, the first kilns soon appeared. They were dug in the ground and covered with a dome (Fig. 2). At first, such kilns were single-chamber; that is, the products and the fuel were not separated. But already in 3800 BC in Mesopotamia, two-chamber kilns were built, making it possible to burn ceramics without leaving traces of soot and cinder on the final product. Those kilns could be heated to a temperature of about 1000°C, which helped the ceramics to become glass-like in structure. At this temperature, almost all possible transformations of clay substances occurred: the smallest clay particles sintered and ensured the strength of the ceramic; it became possible to decorate products with coloured clay and gently fire them, without deforming or soiling them in the process (Ranjbaran & Sotohian 2015; Moradi *et al.* 2018; Aldanov 2020). In double-chamber kilns, it became easier to

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

maintain a more uniform temperature during the firing process. This became a strong impetus for the development of ceramic crafts, for example, in the Minoan civilization (Fig. 3). The Minoan potters could, on the one hand, make large and complex clay products, such as ceramic bathtubs and domestic stoves for heating homes, and on the other hand, they could make micro-ceramics.

Fig. 1. Firing in the bonfire: pots prepared for firing (Peru, South America).

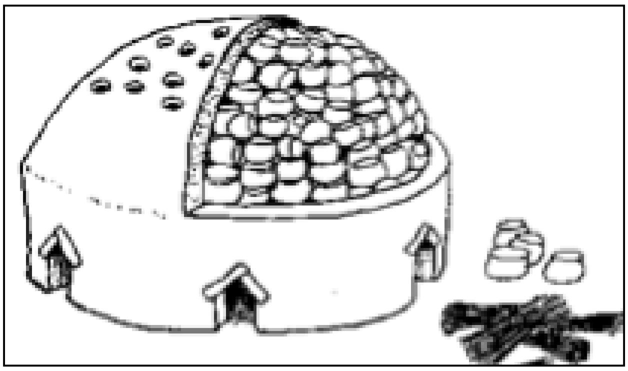

Fig. 2. Reconstruction of a primitive dome-kiln.

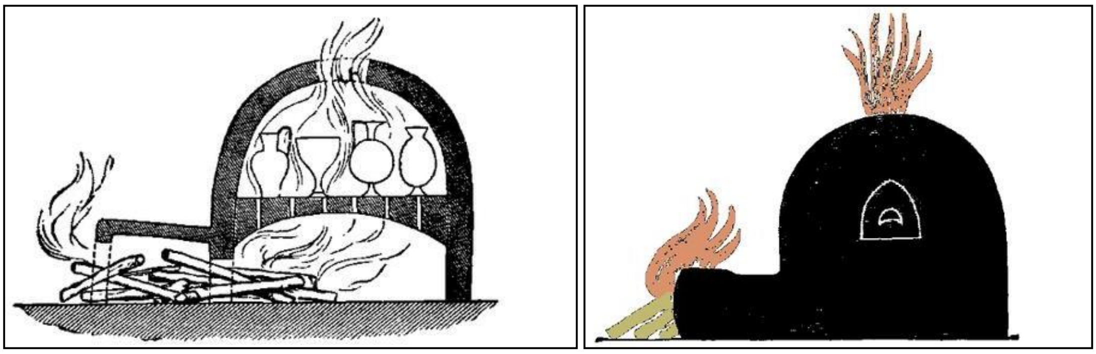

Fig. 3. Scheme of a two-chamber Minoan-Greek kiln.

This type of two-chamber kiln with a perforated ceiling in the lower chamber, which is the floor of the upper chamber - arose in Mesopotamia, and was then used in Ancient Rome. Two-chamber kilns were also used in ancient Greece, improved by a door in the kiln, which made it possible to load in a new batch of ceramics while it was still hot. This helped to conserve heat and enabled a continuous firing process (Fig. 4). The basis of the success of ancient Greek and Roman ceramics lay in the high-tech level of the development of the kilns.

This is what allowed the Greeks and Romans to produce large products of a complex shape with varied designs. The aesthetic peak was reached in the 4^{th}–3^{rd} centuries BC. It was at this time when the masterpieces of Hellenistic ceramics were created (Aldanov 2020). The technical development of kilns led to people beginning to make and use bricks for building houses, and hence overall construction increased as well. Kilns for heating and food preparation were laid out in stone-made.

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

Fig. 4. Two-chamber pottery kilns on a plank from Corinth (Paris, Louvre Museum)

Dwellings; they did not require high temperatures, but had their own particular drawbacks: they were very costly for fuel, they required precaution in operation, and they also needed a device for removing smoke from rooms (Fig. 5). Minoan civilization was also distinguished by the creation of mobile ceramic kilns, which were then adopted by the Greeks. For example, terracotta stands were used for frying skewers over embers. Despite the simplicity of their functions, these products already had a decoration in the form of bullheads on the sides, and convenient handles for carrying the stands to the fire.

Fig. 5. Oven in a Roman bakery. 1^{st} – 4^{th} centuries AD.

Greek portable kilns continued to develop: the kiln became lighter and handles for carrying appeared (Fig. 6). Most importantly, channels appeared at the base through which oxygen passed to the fire source, which supported the combustion process. The upper clay half-dome prevented excessive cooling and heat loss (Http: //ergou.simor.ntua.gr).

The development of technology influenced the development of culture and art:at a certain stage of ancient Greek civilization, such devices were so widespread that they were imprinted by artists on murals and vases (Fig. 7).

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

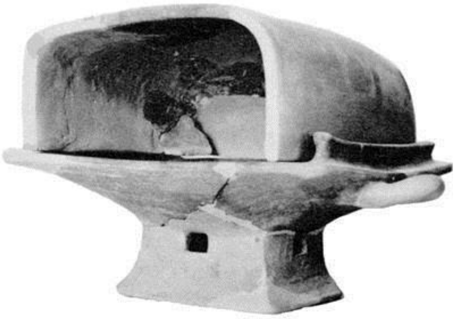

Fig. 6. Portable firing kiln (ancient Greece).

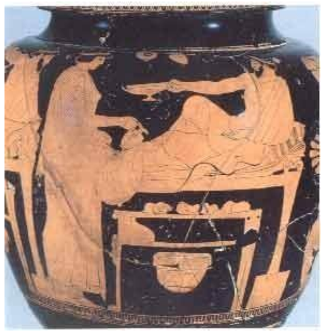

Fig. 7. Picture of a brazier on a vase (ancient Greece).

The civilizations of Japan, China and Korea each developed in their own way. Around 2000 BC the Chinese formed the design of closed kilns, which allowed them to fire products at a temperature of 1000°C. This made it possible to increase the impermeability of fired products and caused the rapid development of the art of ceramics. Such kilns were dug either vertically into the ground, or horizontally into the slopes of the hills. Thanks to this, the source of fire and the fired products were separated, making it possible to increase the temperature in a more controlled manner. The development of firing technology in the hills between the 5th – 3rd centuries BC led to the invention of a new type of kiln, making possible temperatures of above 1200°C. This was a real technical breakthrough which made possible the mass production of porcelain, as it is precisely at temperatures above 1200°C that the chemical reactions necessary for the production of porcelain take place. Those kilns were similar to the ancient Greek dome kilns, but consisted of many domes and were more extensive. These kilns, called "dragon kilns", spread throughout southern China and Korea. The Chinese "dragon kiln" could reach 80 meters in length and hold up to tens of thousands of objects. The size of the kiln meant that the whole community would be involved in pottery making. At that stage in the development of ceramics in China, this was a plus: the kiln did not have to be heated many times to burn a large number of products, which saved both fuel and the efforts of craftsmen. After firing the products in the first compartment, the heated air from it was driven into the second compartment; this second compartment was additionally heated until the products in it were ready; then the air was moved into the next compartment of the kiln. (Fig. 8). A small workshop was not enough for such a kiln; specialization was already required here, which contained the beginnings of pottery production industrialization.

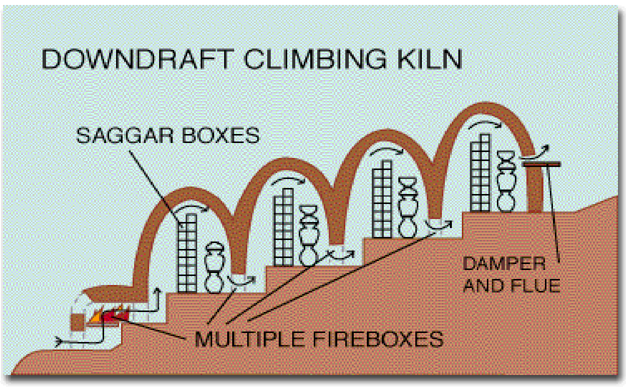

Fig. 8. Scheme of the Dragon Kiln, (also known as "Climbing Kiln").

In Japan, pottery kilns were modified into small, single-chamber kilns "Anagama" (Fig. 9) and multi-chamber kilns ("Noborigama"). In the "Anagama" kilns there was no separation between the source of the fire and the area where the products were fired.

Products in such a kiln were naturally covered with a glaze of ash, and each product looked different depending on what position it occupied in relation to the source of fire during the firing process. Loading the "Anagama" kiln requires experience and skill because the potter must imagine the path of the hot air passing through the kiln, and, in accordance with his artistic plan, arrange the products correctly when firing (https://en.wikipedia.org).

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517
Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI:
Article type: Research

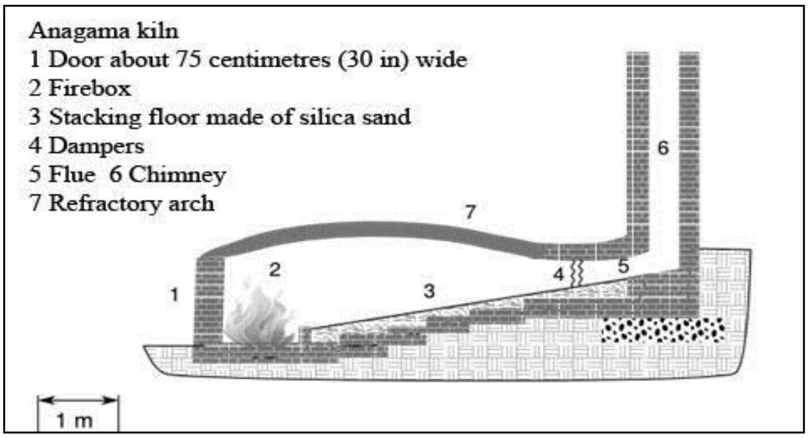

Fig. 9. Japanese "Anagama" kiln.

At the same time in the north of China, another type of kiln appeared, formed from steam ovens for baking bread. Because of the similarity of form with buns, they were called "Mantou" (Fig. 10).

Fig. 10. "Mantou" kiln of the Qing era (Handan Province, China).

The thick walls of the "Mantou" kilns provided uniform heating up to 1300°C and slow cooling. By the end of the Ming Dynasty in the 16th century, almost all Chinese kilns took the form of a big egg, which made it possible to burn many products at the same time, while being compact and convenient for easy transportation (URL: https:// www.nzdl.org). In China and Japan, working for so long with porcelain made it unnecessary to change the firing technology and the design of kilns. Since porcelain contains more quartz in the composition of the feedstock than ordinary ceramics, when it is fired once at high temperature, it is already sintered strongly enough so as not to let moisture through during the use of products. European clay did not possess such properties, so European potters had to invent special coatings that would protect ceramics from moisture.

In European countries, the development of pottery, and hence, accordingly, the design of kilns, began to change during the industrial revolution rapidly. In the middle of the 18th century in England, a new firing scheme appeared: the two-phase system. It was introduced for two reasons: a change in the recipe of the ceramic clay, and increased quality requirements. Now, firing began to be carried out in two stages: first, undecorated products were fired in the kiln at a temperature of 800-900 °C, then the products were covered with glaze and fired again, this time at full blast. The mechanization of production processes in pottery workshops caused an increase in the production flow, which led to an increase in firing volumes. Because of this, large-sized kilns or several small kilns began to be built nearby, which allowed several different firing processes to be carried out simultaneously.

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

Josiah Wedgwood's invention of temperature measuring instruments made the firing process even more accurate. In the 19th and 20th centuries, kilns continued to be modified. Ovens with a shape similar to that of bottles (Fig. 11) spread in England in the early twentieth century. The construction of the kilns consisted of two layers: the outer layer, made of brick (the thickness of the wall reached 0.5 m), and the inner layer, in which there were products for firing.

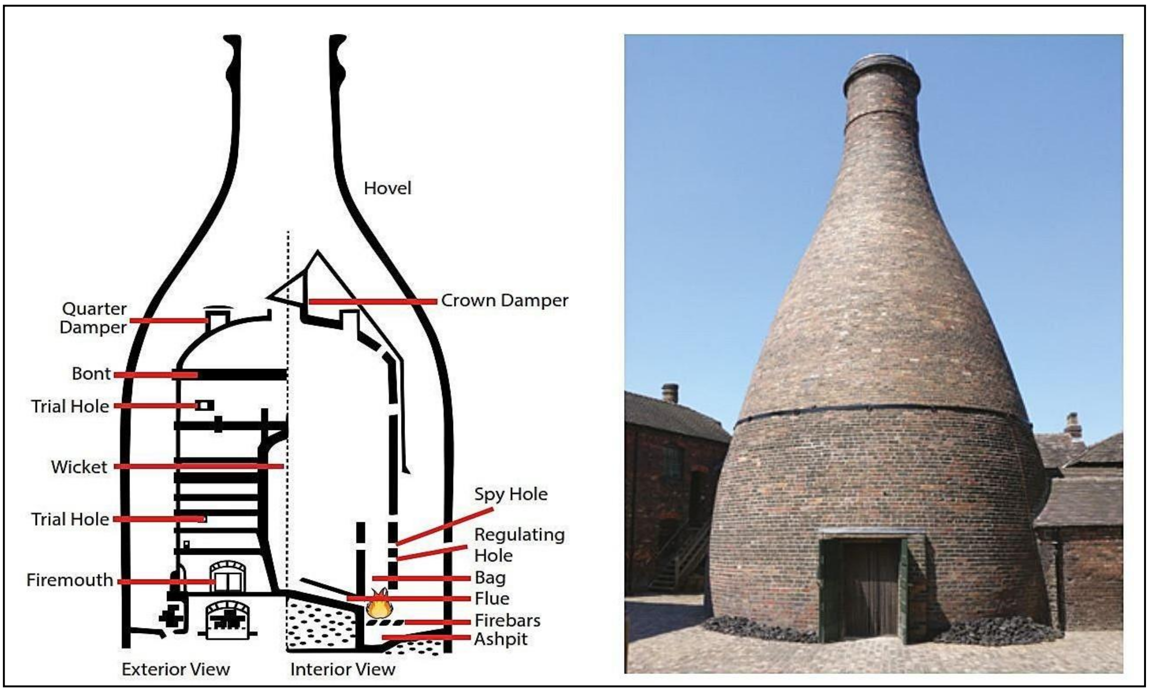

Fig. 11. Appearance and cross-section of the "Bottle Kiln".

The stable design of such a kiln facilitated the placement of ceramic products for firing and made possible temperatures up to 1300°C. The disadvantage of these kilns was that they used coal and wood for fuel. Therefore, in the middle of the 19th century, simultaneously in different countries, experiments began on the use of electricity and producer gas when firing ceramics. The next step in the development of the design of ceramic kilns was the transition to tunnel and ring kilns (Fig. 12), which had a continuous firing process. Such kilns, in essence, constituted an entire factory. In these kilns, products were continually moving in the inner space, and the maximum firing temperature was consistently maintained. The first ring kiln with a series of holes through which fire was supplied was invented by Friedrich Hoffmann. Later the designs of such kilns were modified more than once, becoming more convenient and economical for large-scale production of dishes and bricks.

Fig. 12. Cross-section of the Friedrich Hoffmann's "Ring Kiln".

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

SUMMARY
In the middle of the 19th century, experiments on the use of gas and electricity in firing ceramics began. The use of electricity has led to a change in the design of the chamber for fired products; the combustion chambers have been replaced by heating spirals built into the walls of the kiln itself. The need for a chimney and valve have disappeared. The heating process is now set by a special controller. The dimensions of the kilns have significantly changed, becoming compact and convenient for transportation. All these advantages have contributed to the development of pottery and facilitated the development of ceramics for all interested people. The modern, electric technology allows the user to get a controlled and predictable result with a minimum percentage of defects (https://bottleoven.blogspot.com).

CONCLUSIONS
After reviewing the history of the development of ceramic kilns, we have come to understand how the development of the technological features of these kilns influenced the craft, art and culture of specific nations and humanity as a whole. The discoveries of the period of the technical revolution changed the field of pottery, making significant changes in the processes of manufacturing ceramic products: pottery, typically such an artisanal industry became maximally mechanized. However, the development did not stop there. Now, we have come full circle: from small home workshops in every village of the ancient world, through large pottery settlements in the Middle Ages, and then the organization of huge standard tableware factories in the age of industrialization, humanity has returned to understanding thevalue of manual labour. Thanks to the small kiln sizes, now anyone can enter the world of ceramics and handcrafted pottery production.

ACKNOWLEDGEMENTS
The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

REFERENCES
Aldanov, S 2020, Thermal technologies of antiquity: kilns and temperatures. Part 1. "The evolution of technology" – URL: https://aldanov.livejournal.com/474169.html (accessed: 21.05.2020).

Aldanov, S 2020, Thermal technologies of antiquity: kilns and temperatures. Part 2. Progress in ceramic kilns – URL: https://aldanov.livejournal.com/476449.html (accessed: 21.05.2020).

Allegretta, I, Eramo, G, Pinto, D and Hein, A 2017. The effect of mineralogy, microstructure and firing temperature on the effective thermal conductivity of traditional hot processing ceramics. *Applied Clay Science*, 135: 260-270.

Ivanova, AG, Nuretdinova, AR, Pyataev, AV, Valiulina, SI, Voronina, EV 2017, Moessbauer Study of Sphero-Conical Vessels from Bolgar. *Journal of Applied Spectroscopy*, 84: 273-277.

Kostadinova-Avramova, M, Jordanova, N, Jordanova, D, Grigorov, V, Lesigyarski, D, Dimitrov, P & Bozhinova, E 2018. Firing temperatures of ceramics from Bulgaria determined by rock-magnetic studies. *Journal of Archaeological Science: Reports*, 17: 617-633.

Moradi, A, Taheri Abkenar, K, Afshar Mohammadian, M & Shabanian, N 2018, Microdust impact on leaf gas exchange parameters in oak species of Northern Zagros forests, west of Iran, *Caspian Journal of Environmental Sciences,* 16: 231-239

Norsker, H 2020, The self-reliant potter: refractories and kilns. – URL: http:// www.nzdl.org/gsdlmod (accessed: 22.05.2020).

Pyataev, AV, Valiulina, SI, Ivanova, AG, Manapov, RA, Voronina, EV 2015, Traditional pottery raw materials of the Bilyarsk monocentric agglomeration. *Bulletin of the Russian Academy of Sciences: Physics*, 79: 1058-1061.

Ranjbaran, M, Sotohian, F 2015, Environmental impact and sedimentary structures of mud volcanoes in southeast of the Caspian Sea basin, Golestan Province, Iran, *Caspian Journal of Environmental Sciences*, 13: 391-405.

Song, XQ, Du, K, Li, J, Lan, XK, Lu, WZ, Wang, XH and Lei, W 2019. Low-fired fluoride microwave dielectric ceramics with low dielectric loss. *Ceramics International*, 45: 279-286.

Sun, X 2019, On the modeling structure treatment in traditional ceramic technology to avoid firing deformation. 9^{th} International Conference on Education and Social Science (ICESS 2019), Francis Academic Press, UK, pp.1571-1575.

Caspian J. Environ. Sci. Vol. 18 No. 5 (Special Issue: Environmental Aspects of Economic and Social Sustainable Development)
pp. 509~517 Received: June 12. 2020 Accepted: Dec. 09. 2020
DOI: Article type: Research

اثرات زیست‌محیطی تکامل فناوری‌های پخت در سرامیک

گالنارا ایلیداورا سالفینا*[۱]، اولگا بوریسوونا اوشاکووا[۲]، فیردانیا دامیرونا مبارکشینا[۱]، ایلدار شوکتوویچ سفین[۳]

۱- گروه طراحی و هنرهای ملی، IFMK، دانشگاه فدرال کازان، کازان، روسیه

۲- گروه سازه‌های معماری و ساختمان، دانشگاه دولتی معماری و مهندسی پترزبورگ، سن پترزبورگ، روسیه

۳- گروه رادیوفوتونیک و فن آوری های مایکروویو، KNRTU-KAI، دانشگاه فنی تحقیقات ملی کازان ، کازان، روسیه

(تاریخ دریافت: ۹۹/۰۳/۲۳ تاریخ پذیرش: ۹۹/۰۹/۱۹)

چکیده

سرامیک‌های صنعتی، یکی از متداول‌ترین مواد بوده و شامل فلزات شیشه‌ها و پلاستیک‌هایی هستند که به‌منظور حفاظت از محیط‌زیست و نیز کمک به احیای اکوسیستم‌های تخریب‌شده استفاده می‌شوند. این مقاله به بررسی تاریخچه‌ی توسعه‌ی سفالگری با تأکید ویژه بر سازماندهی فرایندهای فناوری پخت محصولات سرامیکی و نیز اثرات زیست‌محیطی آن‌ها می‌پردازد. برای تولید محصولات سرامیکی با دوام، لازم است تا طراحی کوره بهبود یابد و دمای پخت افزایش یابد که این فرایند موجب تولید کوره‌های خاص می‌شود. برای مدت زمان طولانی، هیزم و زغال سنگ به‌عنوان سوخت در کوره‌های پخت استفاده می‌شد. سپس، تسلط بشریت و انسان بر محیط‌زیست افزایش یافت و سوخت‌های مایع و گاز در سفالگری استفاده شدند. امروزه، ظهور المنت‌های گرمایشی و حرارتی الکتریکی، موجب ساده‌تر شدن پخت شده است: تجهیزات تنظیم حرارتی کوره‌های مدرن به سفالگران امکان حفظ دمای ثابت را در طول فرایند پخت می‌دهد و این باعث افزایش کیفیت محصول نهایی می‌شود. نتایج این مطالعه، تصویر کاملی از انواع مختلف کوره‌های سرامیکی را با در نظر گرفتن مسائل زیست‌محیطی مربوطه ارائه می‌کند. این مطالعه نشان می‌دهد که چگونه کیفیت محصولات سرامیکی تحت تأثیر کوره‌ها و افزایش دمای پخت قرار دارد و درعین‌حال موجب می‌شود تا آسیب زیست‌محیطی به حداقل رسانده شود. این موضوع هم برای سفالگران آماتور و هم حرفه‌ای در طی فرایند پخت، اهمیت دارد.

*مولف مسئول

Bibliographic information of this paper for citing:

Ildarovna Safina, G, Borisovna Ushakova, O, Damirovna Mubarakshina, F, Shavkatovich Safin, Il 2020, Environmental consequences of firing technologies evolution in ceramics, Caspian Journal of Environmental Sciences, 18: 509-517