EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Application of solid media for enhancing the temperature distribution within a downdraft kiln during clay brick firing

Sopa Cansee* and Adisak Pattiya

Bio-Energy and Renewable Resources Research Unit, Faculty of Engineering, Mahasarakham University, Maha Sarakham 44150, Thailand

Received 18 May 2023
Revised 26 July 2023
Accepted 4 August 2023

Abstract

Industrial production of fired clay bricks typically experiences problems related to the brick quality such as insufficient-firing, over-burning, and distortion due to twisting, bulging, warping or cracking, which affect their color and strength. These issues are derived mainly from the poor temperature control and heat distribution. To mitigate this problem, a simple technique is proposed in this work by inserting solid media between bricks during the firing process. Three types of solid media including alumina balls, clay balls and sandstone sheets were tested. The use of the solid media was found to significantly (93%) improve the temperature distribution in the kiln. The temperature difference between the bottom and top bricks reduced from 344°C (without the solid media) to a minimum of 23°C when alumina balls were applied with the sandstone sheets. The properties of the bricks in terms of water absorption and shrinkage were found to be 11.3-11.9% and 1.3-1.6%, respectively, which are comparable with those of the commercial bricks. Interestingly, the compressive strength of the bricks produced with the aid of the solid media was enhanced significantly, especially when the sandstone sheets were used together with the alumina balls as the compressive strength was double that of the industrial bricks.

Keywords: Alumina ball, Clay brick, Clay ball, Downdraft kiln, Temperature distribution, Sandstone sheet

Nomenclature

V.S.	=	shrinkage by volume	*WA*	=	water absorption of brick
Vf	=	brick volume after firing	W_w	=	weight of brick after immersion in water
Vi	=	brick volume before firing	W_d	=	weight of brick before immersion in water

1. Introduction

Brick is a building material generally made from clay molded into a cuboidal shape produced by firing in a high temperature kiln. It has been extensively used for construction due to its strength, durability, and fire resistance. As one of the leading producers of clay bricks in Southeast Asia, Thailand has brick manufacturing industries spreading across all regions throughout the country. Brick production is more characterized by family-owned businesses than a single large operation. The general brick production process involves the following steps: (1) preparation of clay to be mixed with water, sand, or other materials, (2) molding into blocks or desired shapes using hand-made brick molds or automated machines, (3) solar drying to reduce the moisture content, (4) firing in a kiln, and (5) sorting and packaging. Different types of fuels are employed to achieve the requisite temperatures essential for the firing process in conventional firing techniques, with natural gas and oil ranking among the most commonly utilized. Furthermore, solid fuels, biogas/biomass, and electric power are also employed in certain scenarios for the purpose of heat generation [1]. Most kilns are batch type and apply piled-up rice husk as fuel or firing them in a brick kiln with limited space allowing the combustion gas to flow through the bricks to remove moisture from bricks. The drying phase requires special attention, as it entails extracting a portion of the moisture from the brick to ensure its quality is maintained after the manufacturing process [2]. After that, additional heat is supplied to the bricks in order to change the structure in accordance with the temperature change effects [3-7]. In some areas within the kiln, the temperatures are not stable, which leads to inefficient firing of bricks [3, 6]. The impact of setting density on flow uniformity, pressure drop, pumping power, and convective heat transfer coefficients (CHTCs) is examined. Low-density setting (LDS) results in a more uniform heating of the bricks compared to high-density setting (HDS), as the maximum difference in CHTCs between bricks is approximately 4.39% for LDS and 19.62% for HDS. Optimal firing process performance is achieved at a low inlet air velocity of 3 m/s, while the highest productivity is attained at a high inlet air velocity of 9 m/s [2].

Finally, the brick temperature is gradually reduced to avoid excessive thermal stress in the brick, particularly once the quartz inversion temperature is reached, since shrinkage occurs at this point. It is well-known that firing is the most common method for

*Corresponding author.
Email address: sopa.c@msu.ac.th
doi: 10.14456/easr.2023.43

producing bricks, although it consumes a significant amount of energy and leaves a large carbon footprint [8, 9]. According to references [4] and [10], it is evident that throughout all stages of the process, the primary temperature fluctuations are primarily caused by the introduction of firewood, which subsequently leads to an excessive consumption of this resource. Despite meeting the emission standard for flue gas analysis in most aspects, this kiln fails to meet the standard for CO emissions during the drying process. This is due to the necessity of maintaining low temperatures during this stage to preserve the quality of the bricks, which results in incomplete combustion of the fuel. Most research studies have given an emphasis on the energy efficiency of kiln types, brick manufacturing and their business operations. The specific energy consumption (SEC), capacity and investment costs of different types of kilns are reported by FAO, the state and development issues of the brick industry in Asia [11]. Maithel and Heierli [12] compared the kilns in terms of SEC and reported that the SEC for continuous kilns varied between 0.7-2.5 MJ/kg of fired brick, whereas those of batch kilns were 2.0–4.50 MJ/kg of fired brick. In contrast, tunnel kilns exhibit specific energy consumption within the range of 2.31 to 3.51 MJ/kg [13], varying based on the type of fuel used and the kiln's efficiency. Literature reports brick-specific energy consumption rates ranging from 2.04 to 3.51 MJ/kg [14], and in another source, a specific energy consumption rate of 3.47 MJ/kg is documented [15]. It is worth noting that the specific energy consumption rates for brick manufacturing could be higher when using inefficient kilns [16]. The energy required depends on the type of clay and efficiency of the kilns [17]. Moreover, the development of brick processing can improve the SEC [18-21]. A factsheet of downdraft kilns showed that in general, 80% of the brick products were good, whereas 17% were inferior (under-fired and overburnt) and the rest 3% were lost from breakages [22]. Conventional methods of firing clay bricks frequently encounter difficulties in the firing process, resulting in subpar brick quality due to inadequate combustion within the kiln. Consequently, the firing process plays a vital role as it directly influences the overall quality of the final product [23-25]. The production of inferior bricks is speculated to be due to the poor temperature distribution within the kiln chamber during the firing process. Energy consumption within the bricks and ceramics industry holds significant importance. Therefore, this study proposes an enhancement technique aimed at improving the thermal performance during the cooling process in brick tunnel kilns. Previous research [3, 26-28] has explored the improvement of tunnel kilns by investigating the local multifaceted and area-averaged convective heat transfer coefficients (CHTCs) for longitudinal and transverse bricks arranged in a lattice brick setting using a three-dimensional (3D) computational fluid dynamics (CFD) model. The findings indicate that the pressure drop and convective heat transfer coefficient are strongly influenced by the arrangement pattern. Kilns utilizing a lattice setting, with equal spacing between columns and bricks, achieve the highest convection heat transfer coefficient, shorter production time, and provide a substantial measure of energy savings.

To the best of our knowledge, there is no research study investigating a simple technique of applying solid materials in order to produce clay bricks with improved quality. Therefore, the purpose of this research was to propose a technique of using solid media for assisting the heat distribution within the kiln chamber. Three different solid materials including alumina balls, clay balls and sandstone sheets were investigated, and the results were monitored by the temperature profile across the firing chamber and the quality of the fired bricks in terms of water absorption, shrinkage and compressive strength.

2. Materials and methods

2.1 A survey on industrial brick firing in Thailand

Data from two selected clay brick firing factories that have been in operation for more than 30 years from generation to generation in Roi Et Province and Yasothorn Province of Thailand were collected [29]. Their production capacity is approximately 1 million bricks per month. The kilns were downdraft type, with the upper part being an open square to facilitate bringing in the raw bricks into and taking the fired bricks out of the kilns. At the front part, there is a fuel firing chamber and high-pressure fan to transfer heat to the kiln. The heat is distributed throughout the firing chamber and moves upwards to where the bricks are lined up in the closed space of upper part. The kilns are covered with sand as insulation, causing the heat to return downwards before exiting the chimney behind. The input of heat at only the front of kiln makes it convenient to manage the fuel supply. Mixed wood is used as fuel. However, the heat in the kiln distributes unevenly depending on the location which is near or far from the firing chamber. The survey was performed on the production process, firing process, type of kiln, as well as the quality of bricks, with the focus on square downdraft kiln which is currently popular because of its low cost and easiness to manage. The kiln was developed to solve the problem of pollution, to reduce the use of fuel, and to design a structure consistent with rural areas allowing facile construction and easy fuel supply. The process starts with bringing the bricks into the kiln, igniting the fuel, then performing a firing process consisting of 3 steps; drying, firing, and baking the bricks after which the bricks are removed. It was found that some parts of bricks were broken and not completely burnt; this may be due to the fact that the heat energy was insufficient, and the distribution of heat was uneven. Therefore, there needs to be a study to examine the quantity and quality of bricks from the kiln in relation to the use of fuel, the temperature around the kiln walls, as well as the processes of drying, firing, and baking the bricks.

2.2 The downdraft kiln simulation and testing

Testing was performed on the distribution of heat in order to improve the quality of clay bricks by building the firing chamber to bake bricks with the size of 50 cm wide, 60 cm high, and 40 cm thick, as shown in Figure 1. Clay bricks were used as the building bricks and using the mud for mixture in all six sides. The front part of the firing chamber was built in order to use gas as fuel at the lower part in the middle of the all as the heat-giving area; at the left and the right sides of the wall. It was solid construction. At the rear part, the exit of exhaust was built by connecting asbestos pipes so that the exhaust could be distributed to the higher part. The upper part of the kiln had openable walls so that the bricks could be loaded and unloaded and was made from fiber glass as heat insulation.

Testing was performed by using clay bricks from an industrial factory with reliable potential production capacity. Raw four-hole bricks with the width of 62.59 mm, the length of 136.27 mm, and the height of 53.36 mm, were tested; their average weight was 0.66 kg per brick. Samples were taken to find the moisture and were burnt under 5 different conditions as shown in Figure 2. These five conditions were (a) normal arrangement of bricks under industrial pattern (normal), (b) the insertion of alumina balls into the spaces to distribute heat, (c) the insertion of clay brick balls into the spaces to distribute heat (clay brick ball), (d) the use of sandstone sheets to distribute heat around the walls of kiln, and (e) the use of sandstone sheet together with alumina balls. The selection of materials for heat distribution was performed based on the locally available and cost-effective materials to make them practically applicable in the brick industry. These materials have different thermal conductivity properties for brick firing and by inserting them into the spaces between the layers of bricks and between bricks and walls inside the firing chamber where they distribute temperature evenly inside the brick firing chamber.

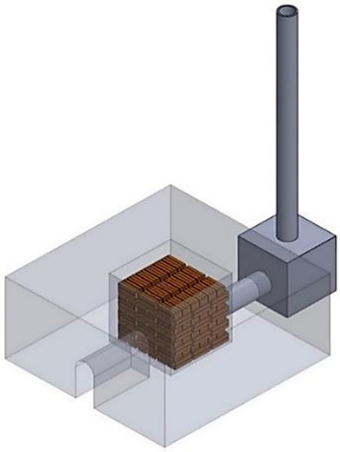

Figure 1 Downdraft kiln with open top model

The number of raw bricks was 158, 139, 135, 130, and 115 bricks for normal, alumina ball, clay brick ball, sandstone sheet, and sandstone sheet with alumina ball, respectively. The number of bricks was different because they were replaced by heat reflection materials with the aim of distributing heat. The bricks were arranged in the brick firing chamber, followed by the installation of k-type thermocouples around the firing chamber, exhaust pipe, at the middle of the lower part and at the upper part of the kiln, as well as the inside and outside of the walls all connected with data logger. Then, a burner was installed at the firing chamber by using LPG as fuel for producing heat energy. Subsequently, the gas was weighed, and the temperature was recorded. The firing procedure consisting of 3 processes (drying, firing, and baking bricks) was then initiated.

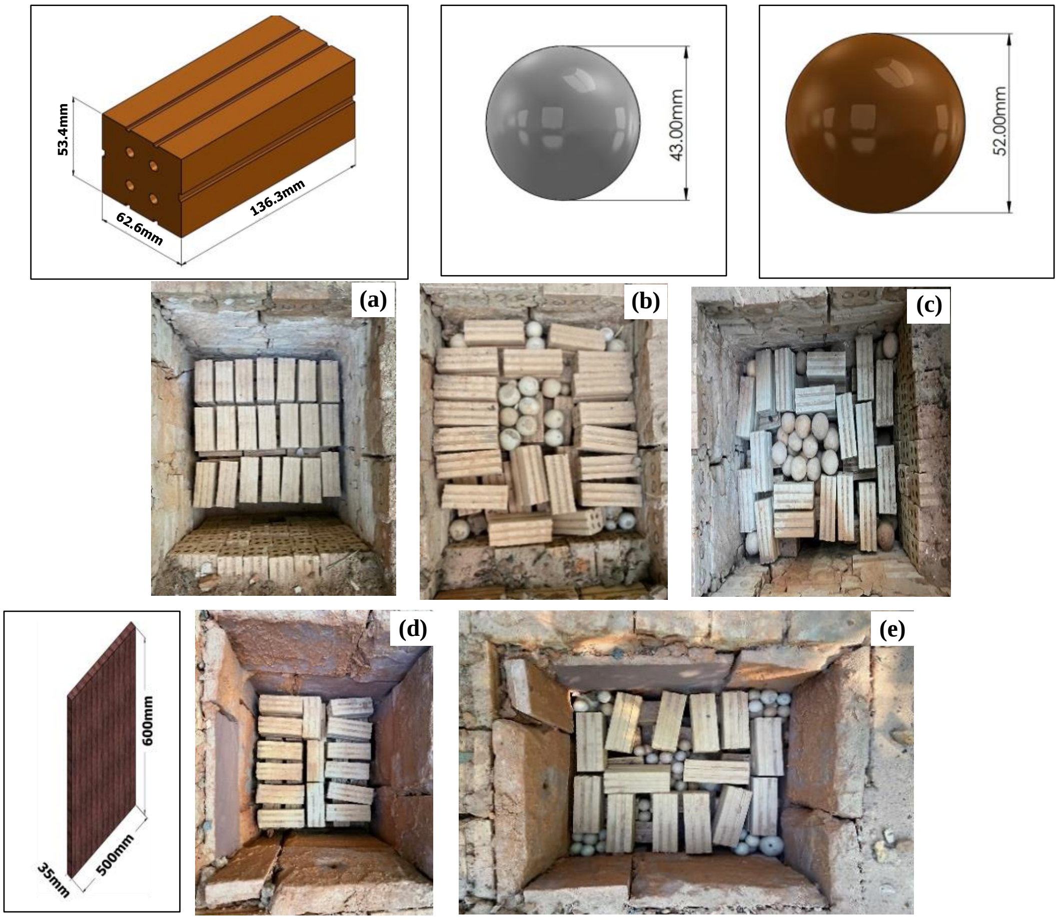

Figure 2 Arrangement the clay bricks: (a) without solid medium, (b) with alumina balls, (c) with clay balls, (d) with sandstone sheet, (e) with alumina ball and sandstone sheet

The drying process was to remove moisture by firing in order to produce heat around the burner, with slight adjustment of gas pressure at the rate of 0.10–0.15 kg/ h to control drying temperature at 200–250 °C. The weight of the gas was recorded every hour and the temperature every 10 minutes. The drying process to remove moisture took 6 hours. Then, the firing process was started to change the structure of bricks by increasing the LPG gas flow at the rate of 1.0–1.11 kg/ h to accumulate the heat to be as high as 800-1,000 °C [17, 30] for 8 hours. The LPG gas was then turned off. and the baking process was started. When cooling down the brick, mud was applied to prevent the sudden drop of temperature which would otherwise affect the structure of the bricks; this step took 12 hours. After that, the firing chamber was opened, and the fired bricks were removed.

2.3 Testing quality of the product

Sampling was performed on 10 brick products obtained under each of the 5 conditions to test the properties of clay bricks including shrinkage, water absorption, compressive strength, and color comparison of the products. The methods used are described below.

2.3.1 Total volume shrinkage

Total volume shrinkage was found by measuring the initial size of the bricks before firing to find width, length, and height, each side for 3 positions, by using vernier caliper. The volume before firing and after firing was then compared using average measurements. The total volume shrinkage can be calculated as follows:
The percentage shrinkage by volume was found by using the equation (1), as follows:

$$V.S.(\%) = \frac{V_i - V_f}{V_i} x100 \quad (1)$$

When, V.S. is shrinkage by volume, V_f is brick volume after firing and V_i is brick volume before firing.

2.3.2 Water absorption

The water absorption (often reported as a percentage) is the ratio of weight of water contained in the brick after immersion in water compared to its dry weight. Water absorption relates to the quality of bricks; good bricks can absorb water of about 10–17 % of the weight of bricks according to the standard for ordinary construction bricks, TIS 77-2531 and TIS 77-2545 [31]. The test was performed by weighing bricks after which they were submerged in water for 24 hours before wiping the surface dry and weighing again. Absorption was calculated using the following equation:

$$WA (\%) = \frac{W_w - W_d}{W_d} x100 \quad (2)$$

When WA= water absorption of brick, W_w = weight of brick after immersion in water, and W_d = weight of brick before immersion in water.

2.3.3 Compressive strength

Compressive strength of brick samples was tested using a Universal Testing Machine of NRI-TS501-100 Brand, TS550011 Model, with maximum compressive strength of 100 kN. Testing was performed by laying samples of bricks on the base and adjusting the distance to be close to the brick samples. After that, the bricks were compressed until they broke at maximum compressive strength. Maximum compressive strength means the ratio of maximum compressive strength to one unit of supporting area and has the unit of N/mm^2 or kg/cm^2.

3. Results and discussion

3.1 Results from the survey of bricks in the industry

Table 1 shows data on the survey of brick firing of two brick production factories in the Northeastern region of Thailand that used downdraft kilns with a square shape opening at the upper part. The volume of the firing chamber was 112.5 and 65 m^3; 50,997 and 31,846 pieces of bricks were burnt equal to the total weight of 56,678.4 and 31,084.3 kilograms respectively for each factory. The firing processes were performed by experts and divided into 3 stages as follows. Baking bricks, by gradually adding the wood fuel so as to gradually increase heat to remove the moisture out of the bricks. In this stage, heat would naturally transfer into the firing chamber without turning on the high-pressure fan. If the moisture of the bricks decreases too rapidly, the bricks would be broken or exploded and damaged since the inside pressure of water contained in the bricks would cause the brick to crack and break. So, in this process, the temperature would be controlled to not exceeding 300–350 °C and would take 18–24 hours; after that, the bricks would be burnt by speeding up the addition of wood fuel and turning on the high-pressure fan to distribute heat in the firing chamber continuously so as to increase the temperature and change the structure of clay into bricks. When the color of bricks indicated that they were completely burnt by emitting heat radiation to the extent that it is possible to see through the rear part, the firing process was finished, and the cooling step was initiated; this step took 3 – 32 hours. Subsequently the kiln was turned off, both through the fuel filling inlet and exhaust chimney in order to bake bricks for 24 – 26 hours. This is to relieve stress from the materials by allowing the temperature to gradually decrease and not to damage the product. However, when testing the temperature inside the kiln both at the left and right sides which are located between the fuel firing chamber of Factory 1 and 2, were between 670 – 965 °C and 538 – 768 °C, respectively. The poor distribution of heat would have affected the quality of bricks such as the incompleteness of firing and the breakages because when the temperature decreases, the structure of raw bricks would not change to become the bricks; this can be observed from the color of the bricks [17]. The rapid increase of temperature in the firing process can cause the bricks to be broken and damaged; the damage proportion is typically about 5 – 7 %. Therefore, if the heat distributed evenly around the kiln, such damage could be reduced, and this would help increase good brick products with acceptable quality.

Table 1 Data of brick firing factories

List of kilns	Unit	Factory 1	Factory 2
Type of brick kiln		Downdraft	Downdraft
Size of brick kiln	m	5x9x2.5	5x5.2x2.5
Wall thickness kiln	m	0.53	0.3
Type of green brick		4 hole, 8 hole	2 hole
Quantity	piece	50,997	13,846
Total weigh	kg	56,678.4	31,084.3
Sum wood fuel	kg	17,480	9,455
Firing process	h		
drying		18	24
firing		30	32
tempering		26	24
Side wall temperature (left-right)	(˚C)	670- 965	538 - 768
Quality brick			
good product	%	94.60	91.18
un-fired	%	3.23	4.74
breaking	%	2.01	3.21
over-burnt	%	0.13	0.87
SEC	MJ/kg	4.34	4.35

3.2 Temperature distribution

The experiments of brick firing included 5 conditions: normal arrangement of bricks under industrial pattern (normal), the insertion of alumina ball into the spaces to distribute heat, the insertion of clay brick ball into the spaces to distribute heat (clay brick ball), the use of sandstone sheet to distribute heat around the walls of kiln, and the use of sandstone sheet together with alumina ball to burn, with the removal of moisture of 14.32 %w.b. by providing heat to bricks from LPG at the low rate of 0.10–0.15 kg/ h for 6 hours. The firing process was started to change the structure of bricks by increasing gas pressure at the rate of 1.0 – 1.11 kg/ h for 8 hours to increase the temperature to be higher so as to change the structure of bricks. The gas fuel was turned off in the firing chamber for 12 hours. Bricks and mud prevented the temperature from dropping too rapidly. After that, the brick products were obtained.

Figure 3 shows that the temperature and time of the firing of bricks were under the following conditions: a) the normal arrangement in the industry and b) the arrangement of bricks together with sandstone sheet and alumina ball to help distribute heat. It was found that the temperatures in the firing chamber were similar (200–250 °C) during firing. However, during the brick firing time, when turning on the gas with increased rate, it was found that firing bricks under the condition of using sandstone sheet to reflect heat together with alumina ball provided rapidly increasing temperature of brick firing around 3.06 °C per minute until the completion of firing time of 8 hours. It was found that the bricks fired with the aid of heat reflection materials caused the heat to accumulate and distribute thoroughly in the firing chamber with the difference of temperatures between the lower part and the upper part of the kiln of only 23.2 °C. However, in the normal firing of bricks, the heat would accumulate more at the upper part and would then spread to the lower part which results in the difference of temperate of both locations for 344.3 °C as shown in Table 2. The different temperatures of the firing chamber during firing when using alumina balls, clay brick ball, and sandstone sheet were 59.1, 100.2, and 298.9°C, respectively. Temperature in the kilns varied between 800–1000°C [32] or 500–800°C [33]. The transformation of brick structure depends largely on different temperature ranges [34]. Therefore, using solid materials to assist heat distribution could cause the temperature inside the firing chamber to more similar heating which positively influenced the quality of brick firing by reducing the inferior bricks such as un-fired, over-burnt or breakages. Upon evaluating the specific energy consumption (SEC) values of bricks, it is evident that they vary at 4.17, 5.40, 5.55, 5.30, and 6.00 MJ/kg, depending on the specific brick arrangements: (a) without a solid medium, (b) with alumina balls, (c) with clay balls, (d) with sandstone sheet, and (e) with both alumina balls and sandstone sheet. The SEC values for brick arrangements devoid of heat-distributing materials closely correspond to those listed in Table 1 for industrial kilns, amounting to 4.34 MJ/kg, which align with the SEC values reported for batch kilns, ranging from 2.0 to 4.50 MJ/kg of fired brick [12]. However, for the remaining arrangements, the SEC values increase significantly due to the replacement of some bricks with heat-distributing materials, creating voids in the brick configurations (see Figure 2) and consequently reducing the overall quantity of bricks. It is noteworthy that the tests employed uniform gas fuel rates for all arrangements, and their durations were equal to assess the implications of temperature distribution on the improvement of brick quality. Increasing the number of bricks while maintaining the heat-distributing materials can be a viable approach to reduce void spaces between bricks and preserve brick quality. Such an adjustment may involve modifying the shape of the heat-distributing materials to resemble the rectangular shape of the fired bricks.

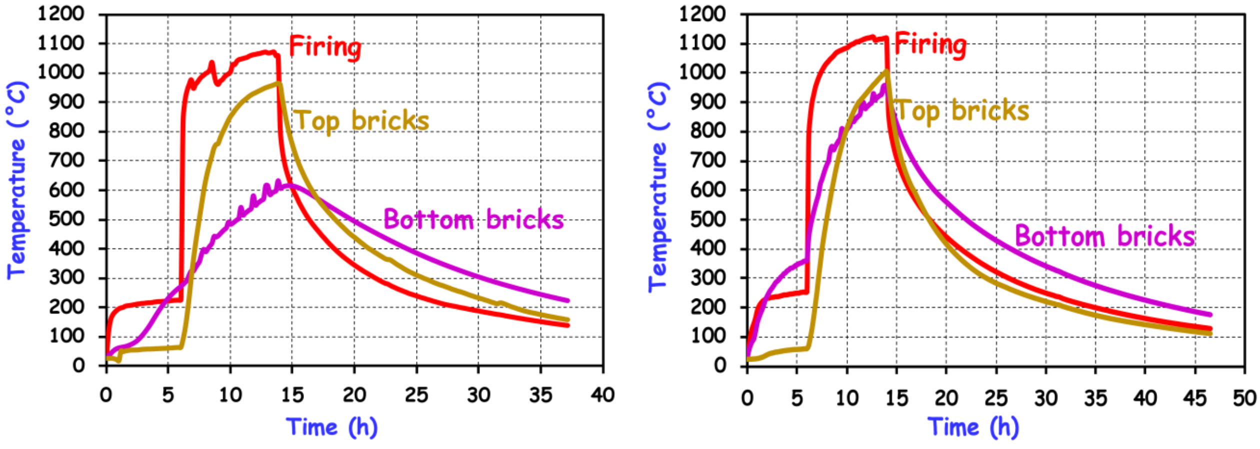

Figure 3 Examples of temperature during the brick firing: (a) without solid medium, and (b) with alumina ball and sandstone sheet

Table 2 The temperature difference between top and bottom brick in firing chamber

Temperature/Condition	Normal	Alumina ball	Clay brick ball	Sandstone sheet	Sandstone sheet and alumina ball
Top brick (˚C)	959.4	985.1	947.4	1044.0	995.6
Bottom brick (˚C)	615.1	926.0	847.2	745.1	972.4
Temperature difference (˚C)	344.3	59.1	100.2	298.9	23.2
SEC (MJ/kg)	4.17	5.40	5.55	5.30	6.00

3.3 Quality of bricks

Clay brick is the fundamental material of construction which has long been used across all regions of Thailand. The quality of bricks depends on soil material in each area, components [20], production technology, and firing temperature [17] used by each manufacturer. The specification of standards set for this industrial product (TIS. 77-2545) is that the quality of water absorption must not exceed 22%. If the water absorption is too high, the built wall will be corroded and molded. Also, the compressive strength must not be less than 10 – 21 kN, depending on the types of bricks and their color which depends on the soil source, and the temperature of brick firing is not specified since it is not the indicator for brick quality. However, in actual use, the wall is always painted to cover the color of bricks.

Table 3 Basic properties of bricks produced with different conditions

Conditions	Absorption (%)	Volume shrinkage (%)	Compressive strength (N/mm^2)
Industry brick	$13.14^a \pm 0.66$	$1.65^a \pm 0.58$	$3.03^a \pm 0.93$
Normal	$11.90^b \pm 0.46$	$1.68^a \pm 0.28$	$3.32^a \pm 0.40$
Alumina ball	$11.31^b \pm 0.63$	$1.65^a \pm 0.53$	$3.45^a \pm 0.39$
Clay brick ball	$11.69^b \pm 0.71$	$1.68^a \pm 0.62$	$4.03^b \pm 0.37$
Sandstone sheet	$11.53^b \pm 0.38$	$1.36^a \pm 0.85$	$4.66^b \pm 0.55$
Sandstone sheet+ Alumina ball	$11.66^b \pm 0.48$	$1.38^a \pm 0.69$	$5.95^c \pm 1.05$

According to Table 3 which describes the water absorption, the shrinkage, and the compressive strength of bricks, it was found that the water absorption of water by brick samples from the factory are the same type as with other brick samples that have higher absorption level with statistical significance of 13.14% compared with controls. This indicates that the porosity of bricks is high, thus they absorb much water. Low firing temperature will cause porosity [15] since there are still air bubbles inside the bricks, whereas the brick samples tested from gas fuel under different conditions have a low water absorption level of 11.31 – 11.90 % and there is no statistical difference, but the quality of all samples was lower than that specified. Water absorption depends not only on the volume of pores and its size, but also on the conductivity between them [34]. Conductivity is highly influenced by firing temperature and the mineral composition, as well as the reaction between minerals when melting [30]. Shrinkage was about 1.36 – 1.68 % when compared with the volume of raw brick (green brick) which is quite low. However, the shrinkage is not an indication of brick quality, but it is related to the dimensional properties. That is, there is a change of size, shape, and volume which is related to the compressive strength. It was found from the brick samples burnt by gas fuel, compared with the industrial brick, that they had higher compressive strength than all samples, and the compressive strength would increase in a way consistent with the firing temperature which is higher than 800 °C. Evening the distribution of heat inside the firing chamber by using the good heat reflection materials inserted in the brick arrangement to distribute heat helps to improve the quality of bricks in terms of compressive strength. The compressive strength of the industrial bricks and the bricks prepared without the use of solid media were 3.03 and 3.32 N/mm^2, respectively.

Therefore, there is no significant difference in using alumina balls. It is possible that there are not many void spaces due to their small size, resulting in low heat transfer, and consequently, the brick's strength is not high. This is consistent with the references [2, 35, 36]. They examined how setting density influences flow uniformity, pressure drop, pumping power, and convective heat transfer coefficients (CHTCs). It was observed that the low-density setting (LDS) resulted in more even heating of the bricks compared to high-density setting (HDS), with the maximum difference in CHTCs between bricks being approximately 4.39% for LDS and 19.62% for HDS. Optimal firing process performance was attained at low inlet air velocity, while high inlet air velocity leads to the highest productivity.However, when the void was increased, the compressive strength was increased to 5.95 N/mm^2 when applying sandstone sheets and alumina balls. Velasco et al. (2015) showed that at the temperature between 500 and 600 °C, the quartz is transformed from α into β. When the temperature reaches 800 and 900°C, a fast shrinkage occurs and vitrification initiates. When cooling down the bricks to 600 and 500°C, free quartz can produce cracks due to the different shrinkage.

If the method proposed in this research is applied in firing a large quantity of bricks at the industrial scale, it will help reduce the number of incompletely burnt bricks which would reduce the loss from each individual firing. According to the data obtained from the survey of brick firing, the number of bricks which are not burnt completely due to the uneven distribution of temperature inside the kiln is as high as 3.23–3.74 % of the total number of fired bricks. In addition, the improved temperature distribution could increase the brick quality in terms of compressive strength. Testing under the stated conditions found that the use of sandstone sheet together with balls in firing bricks would provide the burnt bricks with maximum compressive strength.

4. Conclusions

In this research, the insertion of solid media aimed to assist the heat distribution in the chamber of the kiln for fired clay brick production is proposed as a simple technique for improving the quality of bricks. Low-cost and domestically available solid media used were alumina balls, clay balls and sandstone sheets that had a high potential for reducing the temperature gradient between the top and the bottom bricks. This gradient is known to be a drawback in industrial-scale kilns leading to incomplete, burned or cracked bricks. It was found in this work that the use of alumina and clay balls could reduce this temperature difference from more than 300°C to less than 100°C. By combining the alumina balls with the sandstone sheets, the temperature discrepancy was minimized to only 23°C. Although the use of this solid media could not significantly improve the brick quality in terms of water absorption and volumetric shrinkage, the combination of alumina balls and sandstone sheets was found to be excellent for improving the compressive strength of bricks. The compressive strength of the industrial bricks and the bricks prepared without the use of solid media were 3.03 and 3.32 N/mm^2 respectively. This was increased to 5.95 N/mm^2 when applying sandstone sheets and alumina balls. This indicates that much stronger bricks could be obtained when using this solid media. Therefore, the simple technique proposed in this work can open new applications for fired clay bricks such as load-bearing walls, retaining walls, fireplaces, and other industrial applications.

5. Acknowledgements

This research was financially supported by the Faculty of Engineering, Mahasarakham University, Thailand.

6. References

[1] Araújo MV, Sousa AC, Luiz MR, Cabral AS, Pessoa TRB, Martins PC, et al. Computational fluid dynamics studies in the drying of industrial clay brick: The effect of the airflow direction. Diffusion Foundations and Materials Applications. 2022;30:69-84.
[2] Alrahmani MA, Almesri IF, Abou-Ziyan HZ, Almutairi JH. Effect of lattice setting density on fluid flow and convective heat transfer characteristics of bricks in tunnel kilns. J Thermal Sci Eng Appl. 2020;12(5):051016.
[3] Abou-Ziyan HZ, Almesri IF, Alrahmani MA, Almutairi JH. Convective heat transfer coefficients of multifaceted longitudinal and transversal bricks of lattice setting in tunnel kilns. J Thermal Sci Eng Appl. 2018;10(5):051014.
[4] Suksuwan W, Yeranee K, Wae-hayee M. Environmental impacts and temperature variations in brick firing process in a beehive kiln. Int J Environ Sci Technol. 2023;20:8925-40.
[5] Soussi N, Kriaa W, Mhiri H, Bournot P. Contours of air and brick temperatures inside a tunnel kiln. 13th International Renewable Energy Congress (IREC); 2022 Dec 13-15; Hammamet, Tunisia. USA: IEEE; 2022. p. 1-6.
[6] Al-Hasnawi AG, Refaey HA, Redemann T, Attalla M, Specht E. Computational fluid dynamics simulation of flow mixing in tunnel kilns by air side injection. J Thermal Sci Eng Appl. 2018;10(3):031007.
[7] Dmytrochenkova E, Tadlya K. Simulation of the distribution of air flows and fuel combustion products in a channel of a tunnel kiln. Technol audit Prod Reserves. 2020;3(1):40-3.
[8] Almeida MI, Dias AC, Demertzi M, Arroja L. Contribution to the development of product category rules for ceramic bricks. J Clean Prod. 2015;92:206-15.
[9] Zhang Z, Wong YC, Arulrajah A, Horpibulsuk S. A review of studies on bricks using alternative materials and approaches. Constr Build Mater. 2018;188:1101-18.
[10] Refaey HA, Alharthi MA, Abdel-Aziz AA, Elattar HF, Almohammadi BA, Abdelrahman HE, et al. Fluid flow characteristics for four lattice settings in brick tunnel kiln: CFD simulations. Buildings. 2023;13(3):733.
[11] FAO. Status and development issues of the brick industry in Asia. Field Document No.35. Bangkok: FAO; 1993.
[12] Maithel S, Heierli U. Brick by brick: the herculean task of cleaning up the Asian brick industry. India: Swiss Agency for Development and Cooperation; 2008.
[13] German Federal Environmental Agency. The best available techniques in the ceramic industry (Merkblatt uber die Besten Verfugbaren Techniken in der Keramikindustrie). Germany: German Federal Environmental Agency; 2007.
[14] Mancuhan E, Kucukada K. Optimization of fuel and air use in a tunnel kiln to produce coal admixed bricks. Appl Therm Eng. 2006;26(14-15):1556-63.
[15] Beyene A, Ramayya V, Shunki G. CFD simulation of biogas fired clay brick kiln. Am J Eng Appl Sci. 2018;11(2):1045-61.
[16] Alrahmani M, Almesri I, Almutairi J, Abou-Ziyan H. Combined effect of brick surface roughness and lattice setting density on brick firing in tunnel kilns. Energies. 2022;15(15):5670.
[17] Kumar S, Maithel S. Introduction to brick kilns & specific energy consumption protocol for brick kilns. New Delhi: Greentech Knowledge Solutions; 2016.
[18] Brick Development Association. Brick Sustainability report 2017. London: Brick Development Association; 2017.
[19] Weyant C, Kumar S, Maithel S, Thompson R, Baum E, Floess E, et al. Brick kiln measurement guidelines: emissions and energy performance. Paris: Climate and clean air coalition; 2016.
[20] Murmu AL, Patel A. Towards sustainable bricks production: an overview. Constr Build Mater. 2018;165:112-25.

[21] Hashemi A, Cruickshank H. Embodied energy of fired bricks: the case of Uganda and Tanzania, 14th International Conference on Sustainable Energy Technologies – SET 2015;2015 Aug 25-27; Nottingham, United Kingdom. p. 1-8.
[22] Swiss Foundation for Technical Cooperation, Corporación Ambiental Empresarial (CAEM). Factsheet about brick/Tiles kiln technologies in Latin America. Lima: Swisscontact; 2013.
[23] Refaey HA, Almohammadi BA, Abdel-Aziz AA, Abdelrahman HE, Abd El-Ghany HA, Karali MA, et al. Transient thermal behavior in brick tunnel kiln with guide vanes: Experimental study. Case Stud Therm Eng. 2022;33:101959.
[24] Refaey HA, Abdel-Aziz AA, Salem MR, Abdelrahman HE, Al-Dosoky MW. Thermal performance augmentation in the cooling zone of brick tunnel kiln with two types of guide vanes. Int J Therm Sci. 2018;130:264-77.
[25] Ngom M, Thiam A, Balhamri A, Sambou V, Raffak T, Refaey HA. Transient study during clay bricks cooking in the traditional kiln; CFD numerical study. Case Stud Therm Eng. 2021;28:101672.
[26] Abou-Ziyan HZ. Convective heat transfer from different brick arrangements in tunnel kilns. Appl Therm Eng. 2004;24(2-3):171-91.
[27] Refaey HA, Alharthi MA, Salem MR, Abdel-Aziz AA, Abdelrahman HE, Karali MA. Numerical investigations of convective heat transfer for lattice settings in brick tunnel Kiln: CFD simulation with experimental validation. Therm Sci Eng Prog. 2021;24:100934.
[28] Almutairi JH, Alrahmani MA, Almesri IF, Abou-Ziyan HZ. Effect of fluid channels on flow uniformity in complex geometry similar to lattice brick setting in tunnel kilns. Int J Mech Sci. 2017;134:28-40.
[29] Promtow W, Saenkham S, Butwong N, Cansee S. Performance of a rectangular downdraft open-top kiln for a dual burner. Eng Access. 2022;8(2):325-9.
[30] Velasco PM, Ortiz MP, Giró MA, Melia DM, Rehbein JH. Development of sustainable fired clay bricks by adding kindling from vine shoot: study of thermal and mechanical properties. Appl Clay Sci. 2015;107:156-64.
[31] Thai Industrial Standard. TIS 77-2531 and TIS 77-2545. Bangkok: Thai Industrial Standards Institute (TISI); 2002. (In Thai)
[32] Weng CH, Lin DF, Chiang PC. Utilization of sludge as brick materials. Adv Environ Res. 2003;7(3):679-85.
[33] Shih PH, Wu ZZ, Chiang HL. Characteristics of bricks made from waste steel slag. Waste Manag. 2004;24(10):1043-7.
[34] Cultrone G, Sebastián E, Elert K, de la Torre MJ, Cazalla O, Rodriguez–Navarro C. Influence of mineralogy and firing temperature on the porosity of bricks. J Eur Ceram Soc. 2004;24(3):547-64.
[35] Refaey HA, Abdel-Aziz AA, Ali RK, Abdelrahman HE, Salem MR. Augmentation of convective heat transfer in the cooling zone of brick tunnel kiln using guide vanes: an experimental study. International Journal of Thermal Sciences. 2017;122:172-85.
[36] Refaey H. Mathematical model to analyze the heat transfer in tunnel kilns for burning of ceramics [dissertation]. Magdeburg, Germany: Otto von Guericke University Magdeburg; 2013.