Energy Audit and Improvement of an Updraught Pottery Kiln

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Abstract

Pottery industry is highly energy intensive. Most rural potters depend upon traditional kilns burning firewood with poor energy utilization. This paper presents the work done by the authors towards providing the technical inputs required by a rural industry, such as pottery-making, in reducing their energy costs. Energy audit of two updraught kilns in the field was carried out to identify the causes for their low energy utilization. On the basis of the assessment, an improved kiln was developed which resulted in about 50% savings in fuel as compared to the original kiln of the same volume. The new design also showed a reduction in capital cost of construction. The kiln is very well received by potters in the field.

Keywords: Pottery Kilns, Energy Audit, Rural Industry, Updraught kilns, Heat Transfer Analysis, Terracotta.

Introduction

Upgradation of rural industrial sector is the key to the development of our rural masses and for this, technological inputs are crucial for cutting down the costs, improving the productivity and the quality of the products. Pottery is a product with a substantial potential for income generation for the rural potters due to its appeal in the urban areas. However, it is an energy intensive technology and most of the pottery kilns used traditionally in rural areas have a very poor efficiency. The high efficiency pottery kilns used in the organised sector are too expensive to be affordable by the small scale sector. There is a need for improving the traditional kilns so as to reduce their energy consumption per unit of load substantially without any significant increase in cost.

Traditional Pottery Kilns

The traditional kilns are primarily based on wood as fuel and can be of different types: bonfire kilns, updraught kilns or downdraught kilns [1]. Bonfire kilns, dating back to 10000 years, involve open firing in a shallow pit. Despite flexibility of fuel that can be used, these kilns suffer from low

temperatures of firing, poor ware strength and extensive breakage. An updraught kiln is a cylindrical structure open at the top. Fuel is fired below a perforated platform on which pottery is arranged, and the fire passes upward through the wares, escaping from the top. Updraught kilns exhibit better uniformity of temperature and better retention of heat as compared to bonfire kilns. Pottery temperatures up to 900°C can be attained in this type of kilns, when fired with wood. In these kilns, there is no control over air flow rate, while fuel burning rate is controlled by skilful manipulation of fuel feed rate. The above drawbacks of the updraught kilns led to development of downdraught kilns. In this type of kilns, hot gases produced in a firebox flow upwards to the top of kiln chamber, and are then pulled downwards through the stack of wares by chimney draught, since a chimney is connected to the bottom of the kiln. A damper is provided in the flue channel in order to control the rate of firing and excess air. These kilns exhibit a better uniformity of temperature and lesser tendency for hot spots than updraught kilns. The residence time of gases is higher, and there is better control of firing owing to the presence of chimney and damper. High temperatures upto 1500-1600°C are achievable in such kilns. The cost of construction is much higher than that of an updraught kiln, owing to the height of chimney and mass of masonry in the kiln.

While the above are batch kilns, most modern industrial kilns are continuous tunnel kilns using oil or gas. These are typically 10-30m long tunnels through which the ceramic to be fired is traversed at constant speed on rails, passing through different temperature zones. The efficiency of these kilns is very high. Electric kilns are other high efficiency alternatives available in urban areas mainly for studio pottery. These kilns are quite expensive and need ensured supply of electricity for operation. The industrial and studio kilns are generally used for glazed pottery, which requires temperatures above 1000°C for firing. While rural potters also make glazed pottery, a larger percentage of rural potters make terracotta pottery, which can be fired to good quality at temperatures of upto 900°C. The present work deals with firing of only terracotta pottery.

The Firing Process for Terracotta

After the payload is placed in the kiln, the gaps in the volume are filled with broken tiles and pottery so as to provide a reasonably uniform porosity to the bed and improve the contact between the flue gases and the pottery. Broken tiles and pottery are also placed for covering the top of the payload to a certain depth, so as to enclose the payload completely. Before the final stage of firing, a thin layer of wet clay is plastered on top of the broken tile layer above the payload to further reduce the area available for escape of the flue gases, thereby retaining more heat.

All terracotta pottery is fired at temperatures ranging from 700°C to 900°C. Firing consists of various stages, namely*, smoking, slow firing, rapid firing and soaking*. In *smoking*, the heating is very slow, and pottery temperatures are below 150°C. As the name suggests, the fuel is allowed to burn without a large flame, at very low rates. This is the phase during which the remaining moisture in the pottery is allowed to evaporate, and the low heating rates ensure no cracks due to violent eruptions of water vapour from the pottery. The duration of smoking depends on the bulk of the wares to be fired: the bulkier the ware, longer the smoking. Typical heating rates in smoking range from 0.5 to 1°C per minute. In *slow firing*, volatile matter other than moisture are removed at

temperatures below 450-500°C, at moderate rates of heating with typical temperature rise rates of 1.5 to 2°C per minute. After all the volatile matter is gone, *rapid firing* is done at a high rate so as to raise the temperature of the wares rapidly to 800-950°C. Typical temperature rise rates are 3-4°C per minute. In *soaking,* firing is done at a rate sufficient to maintain the temperature of the wares at the required value over a period of time. The total duration of firing for terracotta wares normally ranges from about 5 to 10 hours.

Rural pottery kilns are invariably batch kilns. Tunnel kilns are not suitable at small scale level due to the higher cost of construction, as well as fuel and the need for continuous operation for them to be economical. Among the batch kilns, downdraught kilns are most energy efficient but most expensive in construction. Thus, updraught kilns appear to be of much greater appeal among the small potters due to their moderate cost with much better performance as compared to low cost bonfire kilns. These kilns are commonly used for firing terracotta ware, and are the focus of the present study. The work presented here involves energy audit studies conducted on two updraught kilns, one at Gramodaya Sangh, Bhadrawati, Maharashtra, and the other at Saathi Samajsewi Sansthan, Kondagaon, Bastar, Chhattisgarh followed by improvements in the kiln at Kondagaon for energy savings.

Description of Studied Kilns

The updraught terracotta kiln used in Kondagaon has a cylindrical volume of diameter 1.83 m and depth of 1.21 m where the pottery payload can be placed for firing on stands or on a grate as shown in Figure 1. In the Kondagaon kiln, no grate was used, and wares were loaded on temporary supports made up of fired terracotta pipes and tiles. A cylindrical wall of the kiln is constructed out of common bricks, and is about 0.46 m (18") in thickness. The floor of the kiln is made of one layer of fire brick. Fuel is fired from fireboxes placed around the periphery of the cylindrical wall as shown in the figure. In the Kondagaon kiln, there were six such firemouths, at 60° to each other.

The updraught kiln studied in Bhadrawati is very similar to that in Kondagaon with a few differences. It has a diameter of 1.52 m and depth of 1.17 m. A fireclay grate is placed 0.5 m above the ground level. The cylindrical wall has a thickness of 0.43 m and there are only three fireboxes at 120° to each other. The fireboxes extend outside the cylindrical wall, and are large enough for large pieces of firewood to be burned comfortably in them. There are a couple of metallic bars placed across the fireboxes acting as a grate in order to support the firewood, providing space underneath for combustion air to enter. The cylindrical wall as well as the firebox are made of an inner layer of fireclay bricks about 10 cm (4") thick, and an outer layer built of common bricks with a 10 cm space between the two layers filled with coal ash as an insulation.

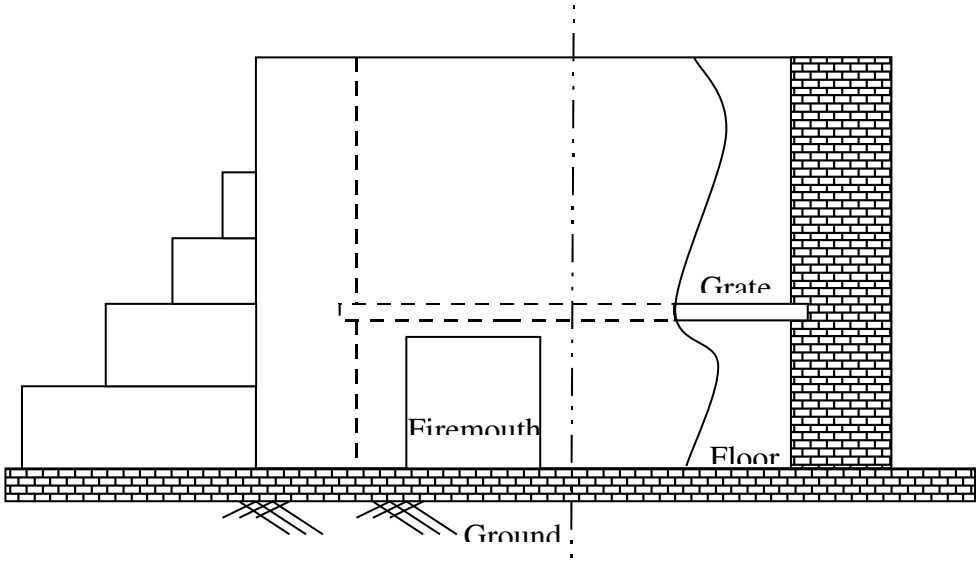


Figure 1. Schematic diagram of an updraught terracotta kiln

Methodology of Energy Audit of Pottery Kilns

A clear definition of the energy requirement is difficult in the pottery kiln energy analysis. The amount of energy required for a particular firing operation includes the sensible energy required to raise the temperature of the ware from room temperature to the maximum firing temperature, as well as the latent energy needed for the removal of moisture, volatiles and the various phase transformations occurring during firing. Literature does not contain quantitative information on the latent components of energy and hence, the accurate quantification of energy required for firing is difficult. In the present work, therefore, only the sensible fraction of energy absorbed by the pottery and the energy needed to remove moisture are accounted for. An attempt is made to determine where all the energy generated due to combustion of the fuel goes during firing. Although this analysis would produce an underestimate of kiln efficiency values, it would throw light on the factors contributing to the increase in fuel consumption and the means that could be attempted to mitigate these factors.

In the present analysis, only the period of firing has been considered, and the quantity of energy absorbed in the various solid parts of the kiln, the energy losses from the flame and other hot parts of the kiln to the ambient and the energy lost through flue gases and ash have been estimated for this period. During the cooling period after firing, some of the energy absorbed by the solid parts of the kiln is likely to be transferred to the payload, but no attempt has been made to estimate this heat transfer.

Ideally, an energy audit should be carried out by measurement of all the components of energy flow in a system. Since both the kilns investigated here are natural draught systems, measurement of air and flue gas flow rates was difficult: this would have been much easier in forced flow systems where airflow could directly be measured at the blower inlet or outlet. Also, it was not feasible to insert thermocouples at all the points where temperature measurements would be desirable. Hence,

some quantities were measured, while some others had to be estimated. The physical systems and phenomena being as complex as they are, several simplifying approximations have to be made, even to estimate various parameters that are required for the energy balance.

The only quantity that was measured was temperature at various points, viz., at the bottom of the payload volume in contact with the fireclay grate, at the top of the payload where the flue gases escape to the ambient, the flame temperature in the firebox, and the brick wall temperatures inside the firebox and on the outer periphery of the cylindrical wall, at intervals of 15 minutes.

The energy terms can be grouped under four major heads: (a) Energy released by combustion of the fuel; (b) Energy absorbed by the pottery; (c) Energy absorbed by the furnace, including the floor below the furnace, the walls of the furnace, the grate, the packing and plastering materials, etc. and (d) Energy lost directly to the surroundings through flue gases and ash, direct radiation from flame and convection from the outer surface of kiln walls. If the measurements and the estimations are accurate, the sum of items (b), (c) and (d) should account for all the energy in item (a). The discrepancy is listed as energy unaccounted for, which was upto about 5.3% of item (a) in the present study.

Energy Audit of Updraught Terracotta Kiln, Kondagaon

Firing and Measurements

The firing of the updraught kiln was started at 1500 hrs on the day of observation. Smoking operation took 180 minutes to raise the temperature to 150°C, after which slow firing phase started. Temperatures rose up to about 300°C in this phase, and this phase lasted 120 minutes. Rapid firing lasted 135 minutes to raise the temperature to 660°C, and the kiln was allowed to cool on its own by natural convection after closing the firemouths with tin sheets to prevent direct draughts of wind from affecting the cooling rates.

For temperature measurement, six thermocouples were used. One 2m-long thermocouple placed at the center of the grate gave the temperature at that location, i.e., the bottom layer of the pottery ware. One ceramic-shielded R-type thermocouple was placed over the fire-box to measure the temperature of the firebox. Four 15 cm long thermocouples were placed at different locations on the wall of the kiln to measure the temperature of the kiln at different depths and heights of the kiln. One thermocouple was used to measure the flue gas temperature. The thermocouples were attached to a digital indicator through a selector switch.

The payload ware to be fired was weighed before and after firing using a balance. The difference was assumed to be the moisture content of the payload, and the other modes of mass loss were neglected. Wood was weighed and batches of 10 kg were prepared. Every time one batch was consumed, the time was noted so as to monitor the feeding rate of wood. Every time firing rate was changed (from smoking to slow firing and rapid firing), the mass of wood consumed during that

phase of firing was recorded. A sample of wood was tested in a bomb calorimeter to obtain its higher calorific value to be 15 MJ/kg. Air flow rate was calculated using this value assuming the firebox temperature to be the adiabatic flame temperature at every instant of time. About 367 kg of wood was used in the firing. Table 1 summarizes some of the details pertaining to the kiln dimensions and firing, besides the material properties relevant to the calculations.

Table 1 Kiln and Payload Details: Original Kondagaon Kiln

Kiln	
Internal diameter	1.83 m
External diameter	2.5m
Height above ground	1.21 m
Width of firemouth	0.33 m
Height of firemouth	0.33 m
Firing	
Mass of the pottery after firing	509.7 kg
Moisture content in the pottery	8% of above
Mass of wood used during the firing	367 kg
Ambient Temperature	25°C
Dead mass	280 kg
Properties of normal brick and ware	
Density	1997 kg/m^3
Thermal conductivity	1.25 W/m-k
Specific heat	880 J/kg-k
Properties of the soil	
Density	2050 kg/m^3
Thermal conductivity	0.52 W/m-K
Specific heat	1840 J/kg-K
Properties of wood	
Lower Calorific Value (as received)	13.545 MJ/kg
Chemical formula	$C_6H_{10}O_5$

Energy Calculations

The following steps show how the various terms pertaining to the energy balance of the kiln are calculated. A summary of the various energy terms resulting from the calculations is presented in Table 2. Detailed data collected during the energy audit of this kiln can be found in Choudhary [2][1].

(a) Total heat released by fuel

The higher calorific value of the fuel was measured in the laboratory using a bomb calorimeter and was found to be 15 MJ/kg on as received basis. During the firing, the moisture formed due to the hydrogen present in the fuel escapes in the vapour form and so does the moisture contained in the fuel. Thus, the heat released by the fuel even for 100% combustion efficiency will be lower than 15 MJ/kg. Assuming the moisture content in fuelwood to be 10% (as received basis), and the hydrogen content of the fuel to be as per the chemical formula given in Table 1, the lower calorific value (LCV) on as received basis is found to be 13.545 MJ/kg. The total heat released due to combustion of the fuel is thus computed in a straightforward manner by multiplying the total fuel consumption by this LCV. This value of 4971.0 MJ constitutes 100% of the energy terms in these calculations.

Total heat released by fuel = 4971.0 MJ (100%)

(b) Heat absorbed by the pottery

Sensible heat absorbed by pottery

The temperature rise in the pottery is not generally uniform. It is observed that generally at the end of firing the temperature difference between the lower most pottery and that at the top is about 150°C. In the present case, the highest pottery temperature at the end of firing in the lower layers was found to be 660°C which indicates the temperatures at the top to be around 500°C. Thus the energy required to raise 509.7 kg of dry pottery from 25°C to the average temperature of 580°C, as calculated using the specific heat of pottery from Table 1 was found to be 248.9 MJ.

Sensible and latent heat absorbed by moisture in the pottery

The mass of the moisture found by subtracting the mass of fired pottery from that of unfired pottery was 8% of the dry ware mass. The energy required to heat this moisture to its boiling point and then to evaporate it works out to be 104.9 MJ.

Total heat absorbed by the pottery = 353.8 MJ (7.12%)

(c) Heat absorbed by the kiln

Heat absorbed by the walls of the kiln

This is determined by the final temperature distribution in the kiln wall at the end of firing. Since the

[1] Some inconsistencies in the data presented in [2] have been corrected in this paper by making appropriate assumptions or approximations.

kiln temperature was only measured at a few points, cue was taken from these values to make a judicious estimate of the heat absorbed by the walls. The temperature measured on the outer surface of the kiln wall showed hardly much rise over ambient temperature, and this suggests that the kiln wall can be treated as semi-infinite. To be able to use standard results for transient conduction in semi-infinite solids, the inner wall temperature must be assumed constant during the concerned period. Since the inner wall temperatures were much lower in the smoking phase as compared to the slow and fast firing phases, the estimation of the heat absorbed by the wall was done separately for the smoking period.

During the smoking period, the wall temperature rises from 25 to 150°C, giving an average wall temperature for smoking period as 87.5^{o}C. Using the assumption of a semi-infinite medium, the temperature distribution in the wall at a given instant can be obtained in terms of error function [3]. This gives the instantaneous heat flux at the wall to be

$$q_w = k_w (T_w - T_i)/(\pi \alpha t)^{1/2} \quad (1)$$

where k_w is the thermal conductivity of the wall material, α is its thermal diffusivity, T_w is the temperature of the inner surface of the wall, assumed constant during the time interval t, and T_i is the initial temperature of the wall before the heating began. The above can be integrated over the time period t and when multiplied by the area of the wall, it gives the cumulative heat transfer to the wall during the concerned time period as

$$Q_w = 2 k_w (T_w - T_i) A_w [t/ (\pi \alpha)]^{1/2} \quad (2)$$

The above gives the wall heat absorption during smoking period to be 68.5 MJ.

During the slow and fast firing periods, the inner surface of the wall was at a higher temperature. While the wall temperature in the firebox was 900°C, in the packed region, the wall temperature varied between 660°C near the grate to about 500°C near the top. The area-weighted average wall temperature was calculated to be 721.9^{o}C and used as T_w in equation (2) for this period which lasted 255 min. Strictly speaking the entire wall at the beginning of the slow firing phase was not at T_i . This aspect has been neglected in this analysis and the wall heat transfer during the smoking phase and the slow and fast firing phase has been just summed up to obtain the total heat absorbed by the wall. For the slow and fast firing phase, the heat transfer to the wall was found to be 908.9 MJ. Thus the total heat absorbed by the wall was 977.4 MJ.

Heat absorbed by the kiln floor

For calculating the heat absorbed by the kiln floor, one can treat the ground below the kiln as a one-dimensional semi-infinite body. Again, the heat transfer was found separately for the smoking phase when the ground surface temperature could be taken as 87.5^{o}C. For this phase, the area of the floor considered was limited to the floor under the inner diameter plus a region under the kiln wall upto half the wall thickness, since the heat is not expected to spread beyond this space. This gave a value

of 42.3 MJ. For the slow and fast firing phase the ground surface temperature was taken as 900°C, and the entire area under the kiln wall was included, since the heat-affected region is larger during this phase. This gives the heat absorbed by the floor during this phase of firing to be 705.2 MJ. Thus the total heat absorbed by the ground was estimated to be 747.5 MJ. The properties of the ground were taken to be that of the soil listed in Table 1.

Heat absorbed by dead mass in the kiln

As mentioned earlier, broken tiles are used as packing material to fill the gaps between wares and ensure uniform porosity of the bed of wares. Broken tiles were also used to cover the top of the wares loaded in the kiln to retain heat and prevent sudden gradients in temperature of the ware due to contact with atmosphere above. Since 280 kg of dead mass was also being heated up from the room temperature to that at the end of the firing, assuming their average temperature to be 580°C, we get the energy absorbed by the dead mass to be 136.7 MJ.

Total heat absorbed by the kiln = 1861.6 MJ (37.45%)

(d) Direct loss of energy to atmosphere

Heat carried away by the flue gases

During firing the mass flow rates of fuel and air as well as the temperature of the flue gases were continuously changing. During the smoking phase, the wood is not allowed to burn with a flame. Most of the volatiles released from wood in this phase leave unburnt. Thus the amount of energy released in this phase is much less than that corresponding to the LCV of the wood. Also, in this phase, the flue gases leaving the upper part of the furnace are nearly at room temperature. Thus, to account for the above observations in the energy balance, it has been assumed that during this phase, the amount of energy released due to combustion is equal to the energy absorbed by the payload and packings (198.7 MJ), wall (68.5 MJ)and the floor (42.3 MJ) totaling to 309.5 MJ. Rest of the energy corresponding to the fuel LCV is directly lost to the ambient. 50 kg of fuel is used during this phase whose heat release potential is 50×13.545 = 677.2 MJ. Thus the direct heat loss to the ambient during this phase is 677.2 – 309.5 = 367.7 MJ.

For the slow and fast firing phases, it is assumed that fuel undergoes complete combustion in the firebox. This is a fair assumption given that the firemouth areas are quite large and combustion is seen to be vigorous during the firing process. No solid residues but ash is found in the remains after combustion. Except during smoking, the combustion is also smokeless.

To account for the change in flue gas temperatures with time, the analysis for the slow and fast firing is done separately. Flame temperature measured during slow firing phase was around 800°C. Estimating the radiation correction in such an environment to be about 150°C, the flame temperature can be taken to be 950°C. A first law analysis of the combustion process assuming it to be adiabatic in the hottest part of the furnace where the temperature is measured, the average air-fuel ratio can be calculated for this phase. The amount of fuel used in the slow firing phase, which lasted 120 min was

80 kg. Taking the specific heat of combustion products at the flame temperature to be 1.3 kJ/kg K [4], the flue gas flow rate is found to be 0.125 kg/s. From measurements the average flue gas exit temperature during this phase was found to be around 275°C. Using specific heat at this temperature as 1.122 kJ/kg K, the energy loss with flue gases for this period is found to be 252.7 MJ. Similarly, during rapid firing, the average flame temperature after radiation correction to the measurements is taken to be 1300°C. The fuel used is 237 kg in 135 min. This gives the flue gas loss in this phase to be 1168 MJ. Thus the total energy loss through flue gases is 1788.4 MJ (35.98%).

Heat lost from the upper surface of the kiln

The flow of flue gases does not happen uniformly over the top surface, but is restricted to some preferred paths due to cracks that occur on the plaster made on the top. The remaining surface loses heat directly to the atmosphere by convection and radiation. For convection, the top surface heat transfer coefficient is computed using the correlation for natural convection over heated horizontal upper surfaces. The average surface temperature of the top surface measured over the entire period of firing is used for calculation of convective losses. For radiative losses, the top surface of the kiln is taken to remain at 500°C during rapid firing phase, and radiative losses during this phase alone are accounted for, since the top surface temperatures are much lower during the other two phases of firing and radiation is negligible. With these, the total heat loss from the top surface comes out to 268.5 MJ by convection and 417.9 MJ by radiation.

Heat lost from the outer surface of kiln walls

As mentioned earlier, the outer surface of the kiln walls hardly rise to significant temperatures above room temperature, and thus, the heat loss from the kiln walls to atmosphere by convection and radiation are small. Since the duration of the firing process is long and the outer surface area of the kiln is large, this loss has been accounted for to complete the energy balance. Using correlations for natural convection from a vertical cylinder [3] for convection and neglecting radiation, the total heat loss from the outer surface of kiln walls is estimated to be 31.2 MJ.

Direct radiation heat loss from the flames

Direct radiation heat loss from the flames to the surroundings is obtained using the mean beam length method [3] applicable to isothermal gray gas emissions. Taking the sooty gas to have a volumetric absorption coefficient of 0.05, flame temperature to be 1000°C, and the gaseous volume of the flame to be a sphere of 0.33m diameter, the heat leaving through the frontal area of the fireboxes is computed to be 16.3 MJ.

Total heat lost directly to atmosphere = 2394.7 MJ (48.17%)

The sum of all the items (b,c and d) above accounts for 95.31% of the heat released by combustion (item a).

Unaccounted losses = 4.69%

Energy Audit of Updraught Kiln, Bhadrawati

An experiment similar to that reported above was carried out on an updraught kiln installed at Gramodaya Sangh, Bhadrawati. In this kiln, the smoking operation took about two and a half hours raising the temperature to about 150°C. Subsequently the slow firing phase started which continued for two and a half hours raising the temperature to 400°C. This was followed by rapid firing which continued for 70 minutes. After this, the kiln was allowed to cool on its own by natural convection as was the case with the kiln in Kondagaon.

The energy audit of the Bhadrawati kiln was carried out before that of the Kondagaon kiln, and the calculations that were done used methods less rigorous and more intuitive than that outlined above. The energy distribution in various components for this kiln is given in Table 2. In this kiln, there was a separate fire clay grate weighing about 365 kg, which absorbed a substantial part of the energy released. The fraction of the energy absorbed by the pottery was lower in this kiln as compared to the Kondagaon kiln. The energy absorbed by the floor in this kiln is much higher than that in the Kondagaon kiln. This is because of the extra bricks laid on the floor to make channels for flue gases from every firemouth to the payload. The detailed data and calculations for the energy audit of this kiln can be found elsewhere [5].

Table 2 : Comparison between Energy Distribution in Different Kilns

Component of Energy Flow	Kondagaon Kiln	Bhadrawati Kiln	Improved Kiln
Mass of payload (after firing)	509.7 kg	182 kg	1000 kg
Mass of wood used	367 kg	200 kg	350 kg
Mass of wood per kg of payload	0.72 kg	1.10 kg	0.35 kg
Total heat released by fuel	4971.0 MJ	3200.0 MJ	4740.8 MJ
Heat absorbed by the pottery			
(a) Sensible Heat absorbed by pottery	248.9 MJ (5.01%)	80.1 MJ (2.50%)	599.3 MJ (12.64%)
(b)Sensible & Latent Heat absorbed by moisture in the pottery	104.9 MJ (2.11%)	52.0 MJ (1.62%)	204.1 MJ (4.31%)
Heat absorbed by the kiln			
(a) Heat absorbed by the walls of the kiln	977.4 MJ (19.66%)	858.0 MJ (26.81%)	729.8 MJ (15.39%)
(b) Heat absorbed by the kiln floor	747.5 MJ (15.04%)	1183.2 MJ (36.97 %)	717.5 MJ (15.13%)
(c) Heat absorbed by dead mass in the kiln	136.7 MJ (2.75%)	39.5 MJ (1.23%)	124.1 MJ (2.62%)
(d) Heat absorbed by the fireclay grate	--	293.0 MJ (9.16%)	--
Direct loss of energy to atmosphere			
(a) Heat carried away by the flue gas	1788.4 MJ (35.98%)	646.4 MJ (20.20%)	1441.6 MJ (30.41%)
(b) Heat lost from the upper surface of the kiln			
Convective	268.5 MJ (5.40%)		211.2 MJ (4.45%)
Radiative	417.9 MJ (8.41%)		417.9 MJ (8.82%)

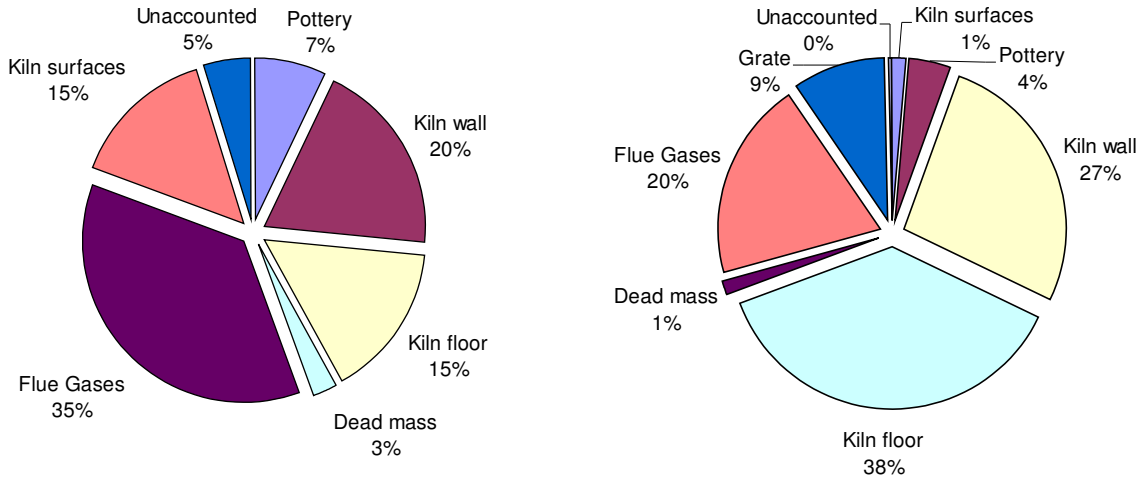
(c) Heat lost from the outer surface of kiln walls (d) Direct radiation heat loss from the flames	31.2 MJ (0.63%) 16.3 MJ (0.33%)	42.9 MJ (1.34%)	30.3 MJ (0.64%) 16.3 MJ (0.34%)
Total energy accounted for	4737.7 (95.31%)	3195.1 MJ (99.8%)	4492.4 MJ (94.76%)
Losses unaccounted for	233.3 MJ (4.69%)	4.9 (0.16%)	248.4 MJ (5.24%)
Energy supplied per kg of payload	9.75 MJ	17.58 MJ	4.74 MJ

Discussion

The distribution of the energy during firing in the two kilns shown in the Table 2 and figures 2(a) and (b) clearly show that the heat absorbed by the pottery is the smallest fraction of the energy accounted for, and that the structure and floor together account for about 35% of the energy released in the Kondagaon kiln and about 72% of the energy released in the Bhadrawati kiln. Hence, the following need to be considered for improving the energy utilization of an updraught kiln.

1. The thermal mass of the structure needs to be decreased. This is possible by reducing the thickness of the walls of the kiln and the density of the material used to build the kiln.
2. The kiln needs isolation from the floor, and firing should be done on grates rather than on the floor.
3. The weight of packing tiles and wares was about 50% of the weight of the payload in both the kilns. This can be reduced by altering the size distribution of the wares to be fired in each batch. Nonetheless, in the present scenario, this only contributes to a small increase in fuel consumption since the energy absorbed by the payload is also small. If the latter increases in an improved kiln, as desired, the energy absorbed by the packing will also increase proportionately unless their amount is reduced.
4. Ensuring a less open flame and better control on primary and secondary air inlet areas, a better control on excess air and flame temperatures could be achieved, which would ensure better combustion and heat release from the fuel. In both the kilns, the flames were almost entirely open to atmosphere, and the air inlet areas in the firebox are very large.

Suggestions 1 & 2 made above have been addressed in the design of an updraught kiln constructed at Kondagaon as part of the present work. The following section describes in detail, the work on the improved updraught kiln.



(a) Kondagaon kiln (b) Bhadrawati kiln

Figure 2. Energy distribution during firing in the two updraught kilns

The Improved Updraught Kiln

The new kiln was developed with the prime objective of decreasing the energy losses due to storage in walls and heat conduction to the ground. The energy absorbed by the walls and floor can be reduced by decreasing the mass of the wall and floor coming in contact with high temperature. This can be achieved by providing a low-cost insulation between the first layer of bricks facing the fire, and the remaining part of the wall or the floor. Several traditional kilns use ash as the insulator. In the new design, the insulation is provided by the air gaps in the floor as well as the wall. The wall is constructed using a rat-trap bonded structure, which provides substantial air gaps in the wall as shown in figures 3 and 4. Figure 3 gives a schematic of the rat-trap bond and figures 4a and 4b show the construction of an actual kiln wall using this structure. The improved kiln was built in Kondagaon with the same interior dimensions as those of the original kiln given in Table 1.

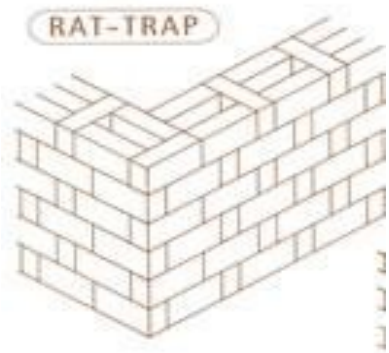


Figure 3: Schematic of rat-trap bonding



(a) (b)

Figure 4. Kiln wall during construction

In this kiln the inner layers of the wall are constructed using the rat-trap bond. The air gap after the innermost row of bricks insulates the rest of the brick structure from the hot inner layer, thereby preventing a large part of the wall from absorbing energy. The rat-trap bonded structure has a thickness of 22.5cm, corresponding to the length of a brick. The width of the brick is 7.5 cm, hence the structure gives air gaps of 22.5cm×7.5 cm×7.5 cm separated by 7.5 cm brick width in the entire wall. This construction reduces the mass of the wall in direct thermal contact with the hot gases. While air gap prevents heat transfer due to conduction, discontinuous gaps keep the convective heat transfer in these gaps low. To increase the strength of the wall, a solid layer of 7.5 cm thickness is provided on the outer side of the wall. The total thickness of the wall in the kiln is thus 30 cm in contrast to 46 cm in the original kiln.

Similarly, the losses from the floor are reduced by making channels of brick structure on the floor. First a continuous layer of bricks is laid on the floor. On top of this, channels are constructed with alternating rows of bricks and air-gap as shown in figure 5. Above this, another continuous layer of bricks is provided to make the floor of the kiln. This construction reduces the contact between the floor of the kiln where fuel is fired and the ground, hence reducing the losses substantially. Figure 6 shows the completed kiln during firing.



Figure 5 Kiln floor during construction



Figure 6. Improved kiln during firing

The reduction in the thickness of the wall results in significant savings. However, if care is not taken, the reduced thickness can cause development of cracks at the firemouths. This is owing to the traditional practice of firing wood at the firemouths. The part of the wall directly above the firemouths is subjected to very high temperature practically all through the firing, and as soon as the firing is complete, it experiences sudden cooling. This, compounded with rat-trap structure of the wall which is both insulating and structurally weaker, experiences higher temperature gradients and hence cracks up. This problem has been overcome by providing a lining of fireclay bricks at the firemouth roof. In addition, three steel belts are tightened around the circumference of the kiln at three heights, from the firemouth to the top as shown in figure 7.



Figure 7. Belt to improve structural strength of kiln

Energy Calculations

Once the kiln was constructed, it was fired with adequate measuring instruments for energy analysis. A payload of dry mass of 1000 kg was put in it for firing. The mass of payload in the kiln depends on the size of the wares fired. In the firing with the new kiln, most of the wares were smaller in size, and so the packing was denser, and the total mass of wares was nearly double of that in the firing of the original kiln reported in this paper. The duration of the firing was the same as before, i.e., 180 minutes of smoking, 120 minutes of slow firing and 135 minutes of rapid firing. Dimensions of the kiln and firing parameters are shown in Table 3. The details of the energy calculations, which were done in a manner similar to the procedure described earlier in this paper, are presented in Table 2.

Table 3 Kiln and Payload Details: Improved Kiln

Kiln	
Internal diameter	1.83 m
External diameter	2.43m
Height above ground	1.21 m
Width of firemouth	0.33 m
Height of firemouth	0.33 m
Firing	
Mass of the pottery after firing	1000 kg
Moisture content in the pottery	8% of above
Mass of wood used during the firing	350 kg
Ambient Temperature	30°C
Dead mass	230 kg

The walls and floor of the new kiln, as mentioned earlier, are not solid brick walls but composite walls with air gaps in the brick. Hence, in computing the heat absorbed by the walls and floor of the new kiln using 1-D analysis formulae (equation 2), effective values of thermal conductivity and density need to be calculated. In the walls, the innermost layer of 7.5 cm thickness and the outermost layer of 15 cm thickness are made of solid bricks, while in the layer between these two, which is 7.5 cm thick, bricks occupy only 25% of the volume. The floor, on the other hand, has the uppermost layer (7.5 cm thick) and the lowermost layer (7.5 cm thick) made of solid brick, while in the middle layer (12.5 cm thick), bricks occupy only 50% of its volume. Thermal resistance offered by a layer of soil 12.5 cm thick below the lowermost layer of bricks was included for calculation of equivalent properties.

Equivalent thermal conductivity was computed by considering the total thermal resistance of the composite wall and evaluating the equivalent conductivity of a solid wall of same dimensions that offers the same thermal resistance. Equivalent density is evaluated by dividing the mass of bricks per unit length of the wall by its total volume. The specific heat is taken to be the same as that of bricks, since the mass-weighting of energy absorbed is ensured by the equivalent density. The equivalent thermal conductivities of the wall and floor work out to 0.7053 and 0.6890 W/mK respectively, while equivalent densities work out to 1636 and 1702 kg/m^3 respectively. The thermal diffusivity values used in computation of heat absorbed by the wall and floor during slow firing and rapid firing were computed from these values. For smoking, on the other hand, since the penetration depth is not large, it is assumed that the properties of brick alone can be used for calculation of heat absorbed in the wall and floor during this period.

Savings

The improved design gives savings in both the capital cost and the running cost of the kiln. The reduction in capital cost is owing to the reduction in thickness of the wall and increased porosity leading to reduction in the number of bricks required for the construction of the wall. The flooring in the new design needs 3 layers of bricks as against a single layer used in traditional kilns. However, the substantial reduction in the mass of the wall more than offsets the increased number of bricks for the floor. For a typical cylindrical updraught kiln of dimensions reported in this paper, the savings in the number of bricks is 32%, amounting to about 1000 bricks less than the traditional kiln, leading to corresponding reduction in construction cost.

The typical fuel consumption in the new kiln has been found to be about 350 kg of wood per 1000 kg of pottery, as compared to about 720 kg of wood per 1000 kg of pottery in the traditional kiln of the same size. The savings in repeated firings have been found to range between 40-60%.

Table 2 gives the comparison between the energy distribution during firing of the different kilns. It can be clearly seen that for unit payload, the new kiln gives nearly 50% savings in fuel as compared to the original kiln in Kondagaon and it consumes nearly one fourth of the fuel used in Bhadrawati kiln. Figure 8 shows the break-up of the energy distribution in the new kiln. It can be seen that the proportion of energy going to the pottery has substantially increased from 7% to 17 %, while those

lost to wall and floor have decreased from 35% to 30 %. Here, these figures should be read in conjunction with the 50% reduction in fuel consumption. Thus, in real terms, the amount of energy absorbed by the walls and floor have decreased from 1725 MJ for 509.7 kg of pottery to 1447.7 MJ for 1000 kg of pottery. Per kg of payload, this translates to a reduction in energy absorbed by the wall and floor from 3.38 MJ to 1.45 MJ, less than half of the original amount. Likewise, flue gas losses decrease from 3.51 MJ to 1.44 MJ per kg of the pottery fired.

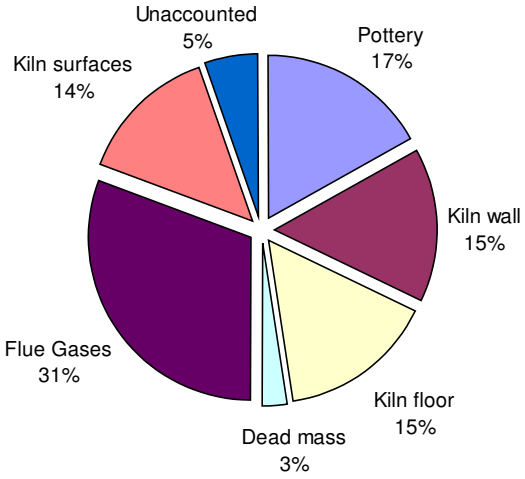


Figure 8. Energy budget of improved kiln

Potential for Impact

The new kilns have been sufficiently tested in the field. Many such kilns have been made by Saathi Samajsewi Sansthan in the Bastar area. So far, 11 kilns have been made by them in Bastar region and 3 more in other places including Goa. In all the sites, potters report substantial fuel savings using the new kiln.

Savings of 40-60% in fuel consumption as compared to the traditional kilns have been reported from the field. Thus, the new design offers a promising alternative for substantial conservation of fuelwood at the national level. Just the Bastar and the surrounding belt have about 5000 kilns. If all of them are converted to new design, it can mean an annual saving of about 75000 tonnes of firewood in that area as estimated from typical number of firings the potters in this area do annually. On an average, one potter can, thus, save about Rs 15000 every year amounting to total revenue saving of Rs 750 lakhs per year in the region. Fuelwood is the main fuel used for pottery firing primarily in the tribal areas close to the forests. Thus, when disseminated nationwide, the improved kiln can result in manifolds saving in firewood for the country besides providing financial benefits to the potters. With the community of potters constituting the second poorest group in the country, this can help a great deal in raising their economic level.

Limitations

While the improved kiln described here is a substantial improvement over the original one, the structure is not as robust as desired. It has been observed that the cracks in the wall first develop above the firemouth where the temperature gradients are high. This is particularly due to the burning fuelwood being placed just below the firemouth. This has been overcome in the later versions of the improved kiln constructed at other sites than the one reported here, by making an arch of fireclay bricks in the area where the flame impinges. Also, the opening up of cracks is prevented by using steel belts around the kiln body. The energy loss through flue gases is still quite high. If the firing rate can be controlled by altering the feeding rates and air fuel ratios, this energy loss can be reduced.

Conclusions

Energy audit of two traditional updraught pottery kilns has been conducted. The results show that a very large fraction of energy gets absorbed by the kiln walls and the floor, and another major fraction of the energy escapes through the flue gases. Only a small fraction is absorbed by the pottery to be fired. Improvements in the kiln have been made for reducing the energy absorbed in the kiln wall and the floor by introducing air gaps and also reducing the thickness of the wall. Use of rat-trap bonding in the wall has helped achieve this. The comparison of the improved kiln with the original kiln shows a saving of about 50% in the fuel consumption per kg of pottery fired. The cost of construction of the improved kiln is lower than that of the traditional kiln owing to less material required for construction. The kiln has been very well received in the field.

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