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Research paper

Revolutionizing Kashmir's tandoor design: improving health, efficiency, and productivity with reduced smoke emissions

Aquib Manzoor Zargar [1], Rayees Ahmad Rather [1], Mohammad Mohsin Khan [1] *

[1] *Department of Mechanical Engineering, National Institute of Technology, Srinagar, 190006, India*
**Corresponding author E-mail: mohsinkhan@nitsri.ac.in*

Abstract

In recent years, the traditional Tandoor, a key tool in bread preparation, has undergone a significant transformation driven by scientific advancements and ergonomic improvements. The conventional Tandoor historically lacked scientific refinement and ergonomic considerations, leading to problems like smoky work environments, direct hand contact with hot surfaces, and substantial heat loss. This study focuses on the innovative redesign of the Tandoor, with a focus on efficiency, health, production, and smoke reduction. The new Tandoor design features a cuboidal core with a deflector at the rear and multiple vertical channels integrated within the oven. These channels significantly increase the bread-baking surface area, with the deflector redirecting flue gases towards them to expedite baking. Bread production benefits from dual heat sources: initial heat from fuel combustion and secondary heat via altered flue gas flow, reducing the average gas temperature from 250 to 180 ºC. Ergonomically, the Tandoor is designed with the outer surface at a convenient 2.5 feet above the ground to improve accessibility for the baker. A strategically positioned chimney effectively directs smoke away from nearby individuals due to its frustum shape. The Tandoor and channels are insulated with Praech, a specialized material to minimize heat loss. Detailed thermal analysis validated the design's efficiency, enhancing baker working conditions while addressing smoke-related concerns and improving production efficiency.

Keywords: *Ergonomic Improvement; Praech Insulation; Production Efficiency; Smoke Reduction; Thermal Analysis.*

1. Introduction

Tandoori roti is a popular Indian traditional product made from whole wheat flour. It is a staple food in most parts of India and other Asian countries [1-3]. According to Khursheed Ahmad, who serves as the secretary of the All Kashmir Local Bread Producers Union (AKLBMU) in 2015, the tradition of Kashmiri Kandur, or bread baking, was introduced to Kashmir by a Sufi saint named Aakhoon Sahib. Aakhoon Sahib had relocated to Kashmir from Kazakhstan, Turkistan, and was renowned for his piety and revered by the people of his time. This practice has been passed down through generations, with the Kandurs considering it not merely a means of livelihood but a way to serve the community. Among various occupational groups, the traditional Kashmiri breadbakers (Kandurs) have been an integral part of Kashmir's daily life for centuries. It has become a customary routine for the average Kashmiri to visit a Kandur shop every morning, shortly after the morning prayer, to obtain traditional Kashmiri bread such as Gerda (circular bread made from fine flour) and Lavasa (circular bread made from flour mixed with curd and baking powder). Additionally, Kandurs prepare "cxhvur" (a type of bun) and "bakerkhani" (a raised bread), which are often enjoyed with tea in the evening. [4-8]. A Tandoor is a cylindrical oven used for baking and cooking. Traditionally, charcoal or firewood is used as fuel in the Tandoor, and bread is baked over a gentle fire. These Tandoors are constructed from durable clay or adobe and resilient fire bricks to withstand prolonged heat. Typically, a fire is kindled within the oven, and once the Tandoor walls have absorbed sufficient heat, the fire is allowed to die down or is maintained at a very low intensity. The ongoing emission of smoke from the oven darkens the walls and ceiling of the bakery. Unfortunately, this setup's lack of proper ventilation poses health risks to the individuals involved in this occupation and their families, resulting in respiratory issues and lung diseases [1, 9-12]. The modern Tandoor design addresses the issue of fuel efficiency. The older Tandoor suffered from incomplete combustion due to limited air circulation within the combustion chamber, leading to excessive smoke production. This not only contributed to environmental pollution but also posed health risks. The outdated Tandoor design wasted over 69% of the heat energy generated during fuel combustion, which was released as unutilized exhaust gases and heat loss through the walls. The problem lay in the inability to recover this wasted heat from the exhaust gases, resulting in a significant loss in Tandoor efficiency [13]. The modern Tandoor design resolves these issues by introducing a rectangular combustion chamber with fuel entry ports and other vents for improved air circulation. It incorporates a diverter that recovers a portion of the heat from the exhaust gases and enhances efficiency. The diverter acts as baffles, facilitating two-pass flows for exhaust gases. This recovers heat and reduces the time required for bread baking, enabling bread to absorb some of the energy directly from the fuel (radiation energy) and some from the exhaust gases. Additionally, the Chimney is designed to prevent smoke accumulation within the shop. The new Tandoor features vertical channels with separators on both channel surfaces to accommodate bread, and rails are provided for smooth channel movement, allowing bread to be easily removed from the Tandoor [14-16].

While tandoor ovens have been linked to significant public health concerns, there is a glaring lack of scientific data regarding their prevalence, the chemical composition of the biofuels utilized in these ovens, and the constituents of tandoor smoke. Consequently, the primary aim of this study is to revamp the current tandoor design, prioritizing improvements in efficiency, health, productivity, and the reduction of smoke emissions.

2. Design of tandoor

2.1. Design of existing tandoor

In Figure 1, we observe an authentic representation of the Tandoor, resembling the surface of a slightly bulging barrel with its narrowest point at one end and its broadest section at the centre. Fuel is ignited at the lower part of the Tandoor, and the resulting heat plays a crucial role in cooking roti. The Clay Tandoor, often called the Kashmiri Tandoor, is known for its simplicity, cleanliness, and reliability. Its widespread popularity is a testament to its exceptional qualities, charm, and versatility. This Tandoor infuses a unique flavour into roti, making it truly distinct [5, 7, 9, 17]. While the Clay Tandoor is a complete unit, it does require an external support structure. Contrary to common belief, installing a clay Tandoor is not straightforward; it involves more than just the clay structure itself. Proper installation demands the expertise of a skilled professional. Our Tandoor necessitates an external backing, such as a brick wall or a metal enclosure, to provide stability and support. Without this external support, it may become susceptible to cracking or making noises when used with charcoal or gas fuel sources.

Table 1: Comparison Of Inner and Outer Diameter with Height of Tandoor In Inches

Width / Outer Diameter	Mouth Inner Diameter	Height
28”	16”	33”
31”	18”	35”
34”	20”	37”
38”	21”	40”

Fig. 1: Old Design of the Tandoor Under Operating Conditions.

2.1. New design of tandoor

The previous Tandoor posed several challenges for the Kandur community, leading to health issues such as respiratory ailments, nasal infections, and vision problems. Its poor ergonomic design also resulted in back problems, ultimately causing orthopaedic conditions among the Kandur workers. Moreover, the necessity to insert bare hands into the hot Tandoor created risks of skin problems, including skin cancer [18-20]. Furthermore, the old Tandoor had a low bread production rate, resulting in long queues as many people had to wait their turn. To address these issues comprehensively, we have developed an improved Tandoor design that mitigates the aforementioned problems. The new Tandoor incorporates the following essential components: Channels, Deflector plate, Basement, Outer shield, Fuel space, Fuel gateway, and Efficient Chimney. This innovative design aims to enhance efficiency, reduce health risks, and increase bread production, offering a solution that significantly improves the working conditions for the Kandur community.

2.2.1. CAD model of channel, deflector plate and chimney

These illustrations depict the three-dimensional configuration of the Tandoor oven. All elements are visible in this design except the fuel door, deflector, and fuel chamber. Eight channels have been incorporated, allowing lateral movement within the Tandoor's width. The channel length is intentionally shorter than the Tandoor's width to accommodate fuel placement behind it. The Chimney has been strategically designed to prevent the accumulation of exhaust gases within the Kandur shop. Using clay, primarily composed of red Alluvial soil, as an insulating material around the Tandoor significantly minimizes heat loss. A protective covering has been applied to both the channels and the inner and outer walls of the Tandoor. This covering consists of a rectangular lattice structure with dimensions carefully selected to minimize heat loss through conduction, convection, and radiation. Additionally, a thin plate is attached to the front side of the lattice, ensuring that it does not fully enter the Tandoor when the channel is closed. The dimensions of the channel have been meticulously chosen to strike a balance; making it too large would significantly extend the bread preparation time. The central portion of the channel is insulated on both sides with a thick layer of clay and additives. A deflector plate is situated at the rear of the Tandoor, primarily serving to redirect exhaust gases towards the channels. Internally, the temperature of these exhaust gases reaches approximately 250 degrees Celsius. The system efficiently utilizes this valuable heat source to expedite the bread baking by redirecting these gases toward the channels. As the exhaust gases exit the external environment, their temperature decreases to around 180 degrees Celsius, ensuring that a portion of the heat is retained within the Tandoor. The deflector plays a pivotal role in harnessing the heat from the exhaust gases to facilitate bread baking. The Chimney is positioned at the top of the Tandoor and is securely attached. Its primary function is to shield individuals in close proximity to the Tandoor from direct exposure to smoke. The Chimney is designed in a frustum shape, with its configuration based on scientific principles to optimize natural draft flow.

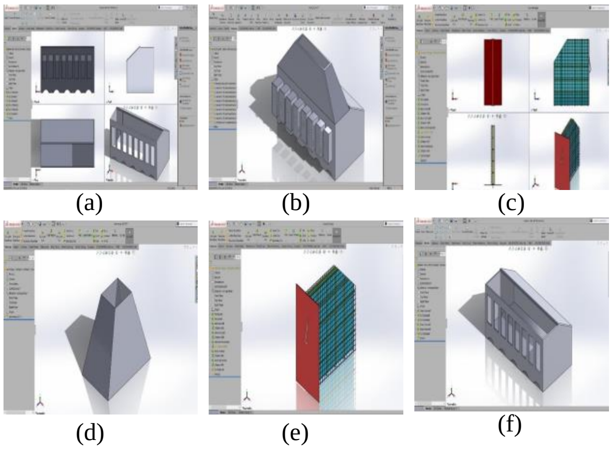


Fig. 2: CAD Model of Tandoor; (A) & (B) Whole Tandoor's Four-Port View and Isometric View, (C) & (E) Channel's Four-Port View and Isometric View, (D) Isometric View of the Chimney, (F) Isometric View of the Skeleton of Tandoor.

3. Experimental analysis

An experimental analysis was conducted to verify whether the issues associated with the previous Tandoor design have been effectively resolved in the new design. This involved constructing and testing the new Tandoor design, albeit with a single channel. It has been assumed that all channels possess symmetrical geometry and share similar properties, making the analysis representative of the entire system. The Tandoor comprises the following components, which are elaborated upon below.

3.1. Fabrication of walls of tandoor, channel, and chimney with insulation

The Tandoor walls are constructed using bricks as the core material. These walls receive protection from both the interior and exterior by applying a special type of clay known locally as "Praech." Praech is a mixture of Red aluvial soil, a specific kind of husk, fabric, and water. To ensure optimal insulation for the Tandoor, the Praech is left to cure for three days. This curing process helps prevent cracks in the insulation material when fully dried. Specific spaces are deliberately left open to accommodate the fuel pathway and the channel. Figure 3 visually represents how the walls were constructed, utilizing bricks and insulation material.

3.2. Temperature measurements

Two instruments were employed to monitor the temperature within the Tandoor: a K-type thermocouple and an Infrared (IR) camera. The K-Type thermocouple comprises two metal alloys, chromel (positive) and alumel (negative), and operates on the Seebeck effect principle. We took approximately ten temperature measurements for various components, including the Channel, Chimney, Flue gases, and Outer wall, and subsequently calculated the average of these readings. The temperature data is presented in Table 2. On the other hand, an infrared (IR) camera is utilized for contactless temperature measurement. Its operation relies on an infrared detector composed of an array of pixels that capture thermal radiation emitted by objects within their field of view. The IR camera collects and focuses this radiation through its lens onto the detector array. The resulting image, known as a thermal image or thermogram, represents temperature variations using different colours or shades.

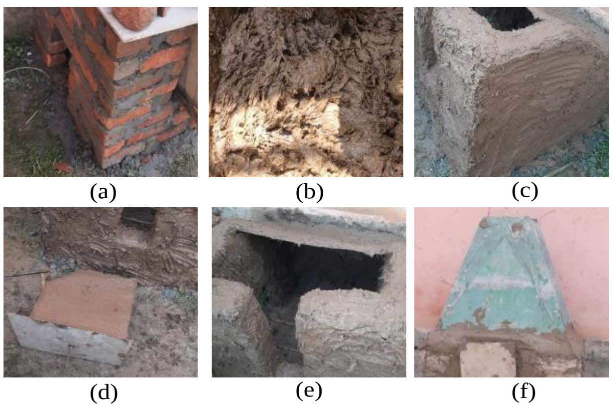


Fig. 3: Six Stages of Fabricating A Tandoor: (A) Bricked-Skeleton, (B) Development of Insulation Material Which Needs to Be Applied Over the Tandoor, (C) & (E) Tandoor Wall with Insulation and Combustion Chamber. (D) Fabrication of Channel with Insulation. (F) Chimney Mounting on the Tandoor.

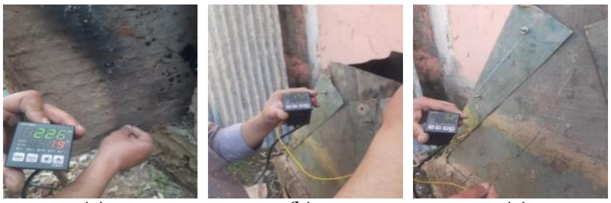
Table 2: Temperature Readings of the Channel, Chimney, Outer Wall and Flue Gases

Parts / Readings	Channel (°C)	Chimney (°C)	Flue gases (°C)	Outer Wall (°C)
Reading 1	254	98	172	26
Reading 2	258	92	158	24
Reading 3	246	82	161	35
Reading 4	240	131	154	41
Reading 5	226	109	170	23
Reading 6	221	79	173	28
Reading 7	201	78	180	24
Reading 8	183	81	159	32
Reading 9	193	86	143	35
Reading 10	180	89	139	20
Average	220.2 °C	83.6 °C	160.9 °C	28.8 °C

4. Results and discussions

4.1. Temperature measurements using k-type thermocouple

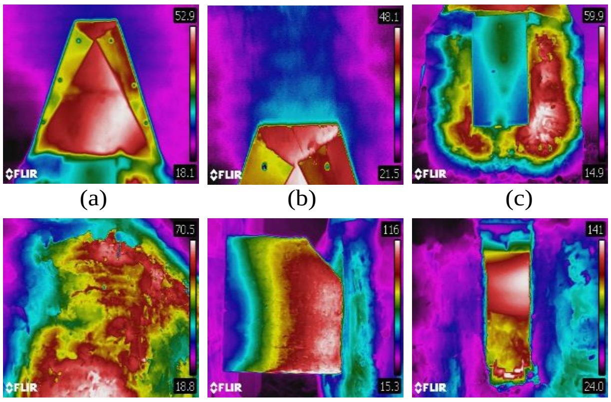
Considerable temperature fluctuations were observed while measuring the channel, flue gases, and Chimney temperatures. Measurements were continued until a steady state was attained. Figure 4 illustrates a snapshot of temperature measurement at a given moment. The average temperature of the flue gases was found to be 160.9°C, while the average temperature of the channel reached 220.2°C.



(a) (b) (c)

Fig. 4: (A) Temperature Measurement Taken for A Channel. (B) Measurement of Temperature for Flue Gases. (C) Temperature Measurement for Chimney.

4.2. Temperature measurements using infra-red camera



(a) (b) (c)

(d) (e) (f)

Fig. 5: Thermal Images Taken After 1 Hour from Combustion of Wood Inside Tandoor; (A) & (B) Temperature Profiles of Infra-Red Images of Chimney and Flue Gases, (C) Temperature Profile of Outer Surface of Tandoor, (D) &(E) Temperature Contours of Channel. (F) Temperature Profile of Tandoor.

4.3. Heat loss calculations

The Tandoor features a triple-layered wall structure. The outer and inner layers consist of clay, comprising a blend of red soil, water, husk, and fiber. Meanwhile, the central layer is constructed using bricks. The deflector is crafted from steel-reinforced concrete, with refractory bricks affixed to its upper surface. Additionally, a chimney is positioned at the upper end of the Tandoor, although it is not depicted in the figures below. The image on the right represents the Tandoor's framework, essentially serving as its core. In simpler terms, it can be likened to the Tandoor's skeletal structure. A small rectangular passage is located near the lower left side, primarily designed for fuel passage. The entrance of the channel on the front side is discernible. On the left side, a layer of clay has been applied to the entire Tandoor, both internally and externally. Heat transfer occurs from the inner and outer walls through the intermediary brick layers. Through experimental observation, it was determined that the temperature achieved at the outer wall was approximately 28 degrees Celsius. This outcome demonstrates the successful ability of this Tandoor design to minimize heat losses effectively.

(a) (b)

Fig. 6: Three Layers of Tandoor: (A) Middle Layer, (B) Outer and Inner Layer of Tandoor.

To determine the heat losses from the Tandoor, including losses across the walls and the Chimney, we can simplify the problem by focusing on a steady-state, one-dimensional heat transfer scenario involving a composite wall consisting of three layers. In this context, we'll consider that two of the layers are made of clay, and the third layer is composed of bricks. The following steps outline the approach:

1) One-Dimensional Heat Transfer Equation (Steady State): We'll utilize the one-dimensional heat transfer equation for each layer to calculate the interface's heat flux.
2) Fourier's Law of Heat Conduction: We'll apply Fourier's law to calculate the heat flux (q) at each interface within the composite wall.
3) Boundary Conditions: To establish boundary conditions, we'll consider the temperatures at the interfaces (T_1, T_2, and T_3) and outer boundaries (T_0 and T_4).
4) Summation of Heat Flux: The total heat transfer through the composite wall is determined by summing up the heat fluxes at each interface (q_1, q_2, and q_3).
5) Calculation of Total Heat Transfer: Once we have the total heat transfer rate (Q_total), we can calculate it by multiplying it by the area (A) normal to the heat flow direction.

Please note that the exact value of q_3 (heat flux at the right interface) depends on the temperature gradient or boundary conditions at that location. To proceed with the calculation, we would need specific information about the temperature distribution or boundary conditions at the right boundary ($x = \delta_1 + \delta_2 + \delta_3$).

This approach simplifies the complex heat transfer problem across the composite wall, allowing us to estimate the heat losses. However, further details and specific boundary conditions would be necessary for precise calculations.

4.3.1. Heat loss from two side walls

The steady-state 1D heat equation for a plane wall can be expressed as:

$$\frac{d^2T}{dx^2} = 0 \tag{1}$$

T represents temperature, and x is the spatial coordinate perpendicular to the wall. This equation signifies that the second derivative of temperature with respect to the spatial coordinate is zero, indicating a constant temperature along the direction perpendicular to the wall.

Consider a wall composed of three layers: two clay layers (right and left) and a central layer of bricks. The wall's right end is at 300°C, the left at 25°C, and the middle layer at 150°C. We need the temperature profile across the wall to calculate the total heat transfer, assuming a linear temperature gradient within each layer.

Let L_1 be the thickness of the right clay layer (0.02 m), L_2 the thickness of the bricklayer (0.1 m), and L_3 the thickness of the left clay layer (0.02 m). The wall's height is 0.6 m. The thermal conductivity of clay is 0.364 W/(m·K), and for bricks, it's 0.5 W/(m·K).

a) In the bricklayer (middle layer), the temperature gradient is given by:

$$\frac{dT}{dx} = \frac{(T_2 - T_1)}{L_2} \tag{2}$$

$$\frac{dT}{dx} = \frac{(150-300)}{0.1} = -1500\ K/m$$

Thus, the temperature profile in the bricklayer is: T(x) = -1500x + 300

b) In the clay layers (right and left), the temperature gradient is given by:

$$\frac{dT}{dx} = \frac{(T_3 - T_2)}{L_3}$$

$$\frac{dT}{dx} = \frac{(25-150)}{0.02} = -6250\ K/m$$

Therefore, the temperature profile in the clay layers is: T(x) = -6250x + 150

To calculate the total heat transfer rate, integrate the heat flux across the wall. The heat flux is determined using Fourier's law:

$$q = -k\frac{dT}{dx} \tag{3}$$

For each layer, multiply the heat flux by the cross-sectional area, which is the height of the wall (0.6 m) times the width of each layer (0.76 m). This results in a cross-sectional area of 0.6 * 0.76 = 0.456 m².

c) In the brick layer:

$$q_2 = -k_2\frac{dT}{dx}A_2$$

$$q_2 = -0.5 * (-1500) * 0.456$$

$q_2 = 342\ W$

d) In the clay layers:

$q_1 = -k_1 \frac{dT}{dx} A_1$

$q_1 = -0.364 * (-6250) * 0.456$

$q_1 = 1340.44\ W$

$q_3 = -k_3 \frac{dT}{dx} A_3$

$q_3 = -0.364 * (-6250) * 0.456$

$q_3 = 1340.44\ W$

The total heat transfer rate is: $q_{total} = q_1 + q_2 + q_3$ (4)

q_{total} = 1340.44 W + 342 W + 1340.44 W = 3022.88 W

The corrected total heat transfer rate across the composite wall is approximately 3022.88 Watts.

For two side walls, the net heat loss will be 2 * 3022.88 W = 6045.76 W (5)

4.3.2. Heat loss from the front wall

In this scenario, we have a plane wall composed of three layers: clay, bricks, and clay again. The heat transfer occurs from right to left, with the right end at 300°C, the left at 25°C, and the middle layer at 150°C. To calculate the total heat transfer rate, we'll consider each layer's thermal conductivity and thickness.
Let's denote the thickness of the brick layer as L_1 = 10 cm = 0.1 m, and the thickness of each clay layer as L_2 = 2 cm = 0.02 m. The total heat transfer rate can be calculated by summing the heat transfer rates in each layer:

$q_{total} = q_1 + q_2 + q_3$

Where, q_1 is the heat transfer rate in the bricklayer. q_2 is the heat transfer rate in the left clay layer. q_3 is the heat transfer rate in the right clay layer.
To calculate each heat transfer rate, we can use the heat equation mentioned earlier.
For the brick layer (layer 1):

$q_1 = -k_1 \frac{dT_1}{dx_1} A_1$

Where: k_1 = 0.5 W/(m·K) (thermal conductivity of bricks). A = 0.84 m * 0.6 m = 0.504 m² (cross-sectional area of the wall). $dT_1/dx_1 = (T_1 - T_2) / L_1$ (temperature gradient, assuming T_1 is the temperature at the right side and T_2 is the temperature at the middle).
For the left clay layer (layer 2):

$q_2 = -k_2 \frac{dT_2}{dx_2} A_2$

Where: k_2 = 0.364 W/(m·K) (thermal conductivity of left clay). A = 0.504 m² (same cross-sectional area as before). $dT_2/dx_2 = (T_2 - T_3) / L_2$ (temperature gradient, assuming T_2 is the temperature at the middle and T_3 is the temperature at the left side).
For the right clay layer (layer 3):

$q_3 = -k_3 \frac{dT_3}{dx_3} A_3$

Where: k_3 = 0.364 W/(m·K) (thermal conductivity of right clay). A = 0.504 m² (same cross-sectional area as before). $dT_3/dx_3 = (T_3 - T_4) / L_2$ (temperature gradient, assuming T_3 is the temperature at the left side and T_4 is the temperature at the outermost left side).
Now, let's calculate the temperature gradients in each layer:

$\frac{dT_1}{dx_1} = \frac{(300-150)}{0.1} = 1500\ K/m$

$\frac{dT_2}{dx_2} = \frac{(150-25)}{0.02} = 6250\ K/m$

$\frac{dT_3}{dx_3} = \frac{(25-0)}{0.02} = 1250\ K/m$

Finally, we can substitute these values into the equations to find the heat transfer rates:

q_1 = -0.5 W/(m·K) * 0.504 m² * 1500 K/m = -378 W

q_2 = -0.364 W/(m·K) * 0.504 m² * 6250 K/m = -721.44 W

q_3 = -0.364 W/(m·K) * 0.504 m² * 1250 K/m = -180.6 W

To find the total heat transfer rate, we sum these values:

$q_{total} = q_1 + q_2 + q_3$

q_{total} = |-378 W| + |-721.44 W| + |-180.6 W| ≈ 1280 W (6)

As expected, the negative sign indicates heat is being transferred from right to left. Therefore, the total heat transfer rate is approximately 1280 watts.

Hence total heat loss from the wall is (5) + (6) = 7325.76 W (7)

4.3.3. Heat loss of chimney and through flue gases

We have a chimney with a frustum shape used to remove flue gases. The average temperature of the flue gases inside the Chimney is 180 degrees Celsius. We are assuming steady-state conditions with no radiation heat transfer. The outer surface of the Chimney has an average temperature of 70 degrees Celsius. The height of the Chimney is 60 cm, and the inlet section of the Chimney has dimensions of 76 cm * 43 cm, while the exit section of the Chimney has dimensions of 27 cm * 23 cm. The Chimney is made of steel with a thermal conductivity of 45 W/mK.
To calculate the heat transfer rate from the surface of the Chimney and at the exit of the Chimney, we need to determine the surface area of the Chimney and use the heat transfer equation.
First, let's calculate the surface area of the frustum of the Chimney using the given formula:

1) Inlet section area (A_1): A_1 = 0.76 m * 0.43 m A_1 ≈ 0.3268 m²
2) Exit section area (A_2): A_2 = 0.27 m * 0.23 m A_2 ≈ 0.0621 m²
3) Thickness of the Chimney (t): t = 0.006 m
4) Inlet Perimeter (P_1): P_1 = 2 * (length + breadth) P_1 = 2 * (0.76 m + 0.43 m) P_1 ≈ 2.38 m
5) Outlet Perimeter (P_2): P_2 = 2 * (length + breadth) P_2 = 2 * (0.27 m + 0.23 m) P_2 ≈ 1 m
6) Slant height of the frustum (L): $L = \frac{h^2 + (A_1 - A_2)^2}{A_1 + A_2}$

$$L = \frac{0.6^2 + (0.3268 - 0.0621)^2}{0.3268 + 0.0621}$$

L ≈ 0.6143 m

7) Surface area (A) of the frustum: A = 0.5 * (P_1 + P_2) * L

A = 0.5 * (2.38 m + 1 m) * 0.6143 m

A ≈ 0.7273 m²

Now, let's calculate the temperature difference (ΔT): $\Delta T = T_{flue} - T_{surrounding}$

ΔT = 180°C - 70°C ΔT = 110°C

Finally, we can calculate the heat transfer rate (Q) using the heat transfer equation:

$$Q = kA\frac{dT}{t} \quad (8)$$

Where, k is the thermal conductivity of steel (45 W/mK), A is the surface area, and t is the thickness of the Chimney.

Q = 45 W/mK * 0.7273 m² * 110°C / 0.006 m

Q ≈ 91650 W (or 91.65 kW)

Therefore, the heat transfer rate from the surface of the Chimney is approximately 91.65 kW.

To find the total heat loss from all the walls and across the Chimney, we can add the heat loss from the Tandoor (7) and the Chimney:

Hence total heat loss across tandoor = (416.74+ 7.32) KW = 424.06 KW (9)

Also, the experiment was performed for only 60 minutes.

4.4. Efficiency of new tandoor

The wood used as fuel in this Tandoor was baghati wood with a calorific value of 19 MJ/kg, and the total quantity of wood used was approximately 7 kg. To find the efficiency, we need to calculate the heat losses through the walls only.

1) Heat liberated by burning 7 kg of wood

Total heat supplied = Calorific value * Quantity of fuel in kg

Total heat supplied = 19 MJ/kg * 7 kg

Total heat supplied= 133 MJ

2) Percentage of heat loss across Tandoor

$$= \frac{Heat\ loss\ from\ the\ walls\ of\ the\ Tandoor}{Heat\ supplied} * 100$$

$$= \frac{(424.06*60)}{133000} * 100$$

= 19.13 %

3) Efficiency of the Tandoor: Efficiency of the Tandoor = 100% - Percentage of heat loss Efficiency of the Tandoor = 100% - 19.13% Efficiency of the Tandoor ≈ 80.86%

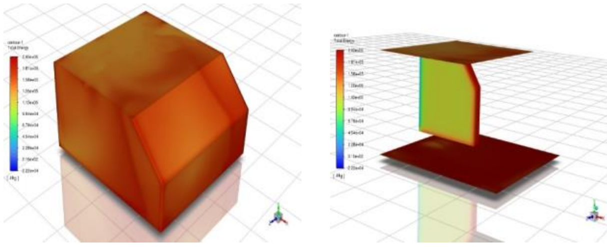
Therefore, the efficiency of the Tandoor is approximately 80.86%.

5. ANSYS simulation for outer wall and channel

All the pertinent calculations, including the determination of convection heat transfer coefficients, specific heat capacity, total energy, and total temperature, were conducted using Ansys Fluent [21]. Since hot combustion gases are generated inside the Tandoor, the fluid properties were carefully selected to match those of actual flue gases. The chosen thermal conductivity was set to 0.0454 W/m·K, and the specific heat was defined as 1500 J/kg·K. The Pressure-Velocity coupling scheme employed was the coupled approach, while the flux type chosen was Rhie-Chow distance-based with Green-Gauss cell-based discretization. A second-order pressure order and second-order momentum using upwind schemes were implemented. Additionally, turbulent kinetic energy and specific dissipation rate were set to second-order upwind schemes. For energy calculations, a second-order upwind scheme was also applied. The solution successfully converged after 250 iterations.

5.1. Total energy of outer wall, channel, inlet and outlet

The highest recorded total energy absorbed by the outer wall reaches 203 kJ/kg, while the lowest recorded value is approximately 22 kJ/kg. Notably, there were observable smooth bands on the exterior surface of the Tandoor, as depicted in Figures 7(a) and 7(b). This wall is configured as a composite structure, featuring clay on its inner and outer surfaces, with a central layer constructed from refractory bricks.

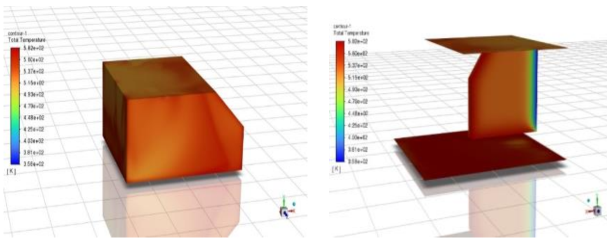


(a) (b)

Fig. 7: (A) Energy Contours on Outer Wall of Tandoor and (B) Energy Contours of Channel Inlet and Outlet.

5.2. Total temperature attained by outer wall, channel, inlet and outlet

The inner surface of the outer wall exhibits a range of temperatures, with the maximum temperature reaching 582 K and the minimum temperature measuring 358 K, as illustrated in Figure 8. Notably, the highest temperature is concentrated on the inner side of the deflector due to direct exposure to flue gases. Smooth temperature bands are discernible on the outer wall, with maximum temperatures predominantly along the bottom edges, gradually decreasing as one moves upward. Temperature contours were also generated for the channel, the lower section, and the flue gas outlet. In particular, the bottom part exhibits a uniform red colouration, indicating the region where fuel combustion occurs and, consequently, the highest temperatures. Moreover, the figure highlights that the right side of the Chimney maintains significantly lower temperatures compared to its left counterpart, primarily because it remains outside the direct influence of the hot flue gases within the Tandoor.



(a) (b)

Fig. 8: Temperature of Outer Wall, Inlet, Channel and Outlet in Figure (A) and (B).

5.3. Total heat flux of outer wall

Heat flux pertains to the heat transfer rate per unit area and represents the measure of heat energy moving through a specified surface within a given time frame. It is quantified in power units per unit area, such as watts per square meter (W/m²). The mathematical expression for heat flux (q) can be derived using the following formula:

$q = -k * \nabla T$

Here, q denotes the heat flux, k represents the thermal conductivity of the material facilitating the heat transfer, and ∇T signifies the temperature gradient across the surface, oriented perpendicular to the heat transfer direction. The inclusion of a negative sign in the equation signifies that heat invariably travels from regions with higher temperatures to regions with lower temperatures. In the provided figure, you can discern the presence of smooth bands depicting surface heat flux.

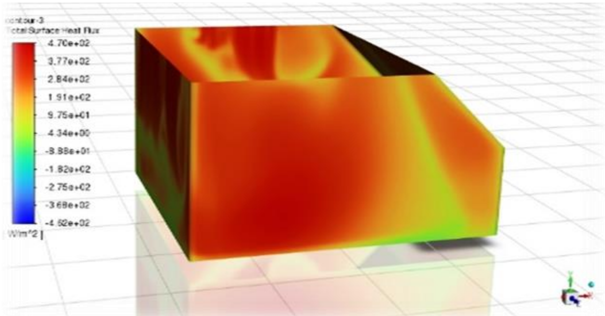


Fig. 9: Heat Flux of Outer Wall.

Figure 9 shows that the maximum heat flux reaches approximately 470 W/m², while the minimum is around 462 W/m². Notably, the lower heat flux is evident on the lower section of the front face. This phenomenon can be attributed to the presence of a channel in this area, which absorbs a portion of heat from the flue gases, resulting in a reduction in heat flux at this specific location.

5.4. Vorticity of outer wall

Vorticity, a fundamental concept in fluid dynamics, characterizes the rotation or circulation of fluid particles within a flow. It's described as a vector quantity and is calculated as the curl of the velocity vector field of the fluid. In simpler terms, vorticity quantifies how fluid elements tend to rotate, and you can observe the vorticity contours in Figure 10.
Mathematically, vorticity (denoted as Ω or ω) is expressed as the cross product between the velocity vector (V) and the gradient of the velocity vector (∇): $\Omega = \nabla \times V$
Figure 10 illustrates the contours of vorticity magnitude.
The vorticity magnitude indicates the strength of rotation, with its direction being perpendicular to the plane of rotation, following the right-hand rule. Positive vorticity signifies counter clockwise rotation when viewed in the direction of flow, while negative vorticity represents clockwise rotation. The maximum and minimum vorticity values are 60.6 and 4.65×10^{-7} s^{-1}, respectively. It's worth noting that the maximum vorticity is located near the upper end of the front side of the Tandoor due to the presence of a channel, which induces vorticity.

5.5. Nusselt number of channel

The Nusselt number (Nu) is a dimensionless parameter employed in the analysis of convective heat transfer. It serves to quantify the ratio of convective heat transfer to conductive heat transfer across a fluid boundary layer, thereby offering insight into the efficiency of convective heat transfer. Mathematically, the Nusselt number is expressed as:

$$Nu = h * \frac{L}{k} \tag{10}$$

Where:

- Nu represents the Nusselt number,
- h denotes the convective heat transfer coefficient,
- L is a characteristic length scale, typically the surface length in the direction of flow and
- k stands for the thermal conductivity of the fluid.

Figure 11 illustrates the variation of the Nusselt number within the channel, providing a visual representation of how it changes at different points within the system.

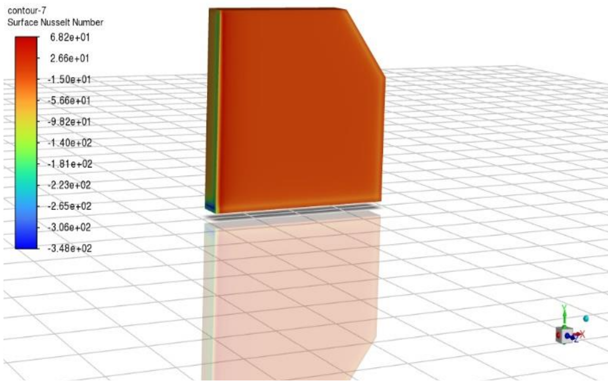


Fig. 11: Nusselt Number Variation of Channel.

The convective heat transfer coefficient (h) characterizes the fluid's capacity to transfer heat through convection, while the thermal conductivity (k) defines the fluid's ability to conduct heat. The characteristic length scale (L) choice depends on the system's particular geometry and flow configuration. The highest Nusselt number value, reaching 68.2, is observed at the channel's surface. Our objective was to enhance convective heat transfer within the channel, and we have succeeded in achieving this goal.

5.6. Post processing images of plane passing through mid-way of tandoor

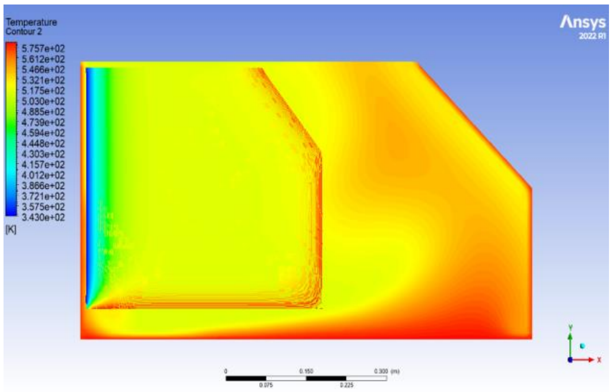


Fig. 12: Temperature Contours of Tandoor Through Mid-Plane.

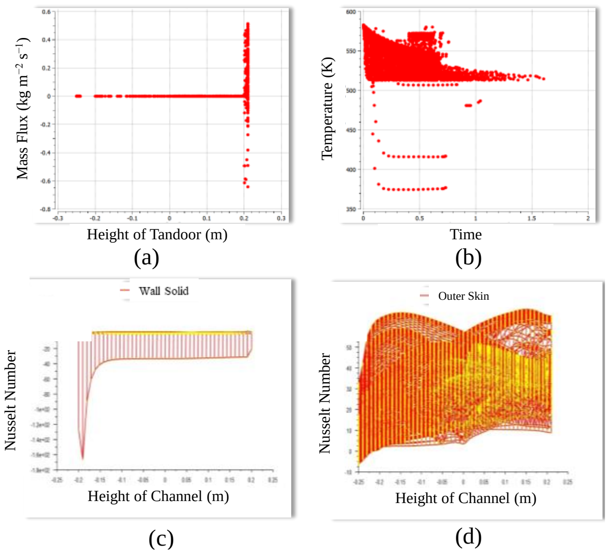


Fig. 13: (A) Variation of Mass Flux with Height of Tandoor, (B) Variation of Temperature of Tandoor with Time, (C) Variation of Nusselt Number of Channels with Height of Channel, (D) Variation of Nusselt Number of Outer Wall of Tandoor with Height of Channel.

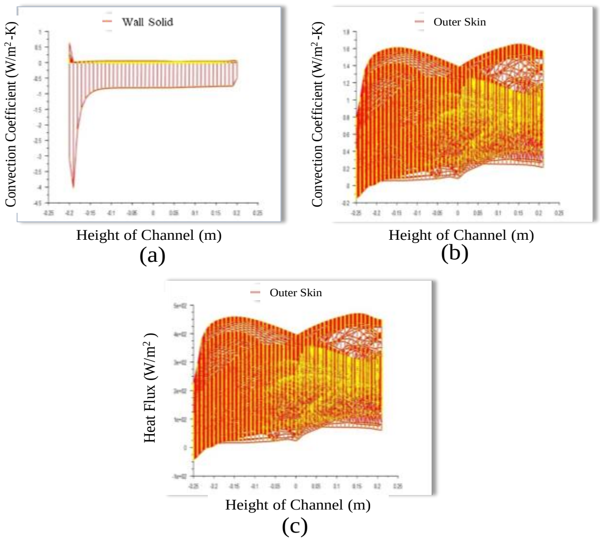


Fig. 14: (A) Variation of Convection Coefficient of the Channel with A Height of the Channel, (B) Variation of Convection Coefficient of the Outer Wall of Tandoor with the Height of the Channel, (C) Variation of Heat Flux of Tandoor with the Height of the Channel.

In the context of ANSYS Fluent, post-processing pertains to the analysis and visualization of data resulting from computational fluid dynamics (CFD) simulations. After conducting a simulation with the ANSYS Fluent software and achieving a converged solution, Fluent offers various tools and functionalities for post-processing the data. This involves gaining insights into flow behaviour, extracting pertinent information, and generating visual representations of the results. Figure 12 illustrates temperature contours along the plane passing through the midpoint of the Tandoor. The temperature contours reveal that the maximum temperature reaches 575.7 Kelvin. In contrast, the minimum temperature, at 340.3 Kelvin, is found near the Tandoor's bottom section and on the channel's left side.
All the pertinent charts are presented in Figures 13 and 14, encompassing the following aspects:

1) The relationship between mass flux and the channel's height.
2) The evolution of temperature over time.
3) The correlation between the Nusselt number of the channel and its height.
4) The Nusselt number of the outer wall in relation to the channel's height.
5) The convection coefficient of the outer wall as it varies with the channel's height.
6) The heat flux of the channel relative to its height.
7) The heat flux of the outer wall with respect to the channel's height.

6. ANSYS simulation for temperature of chimney

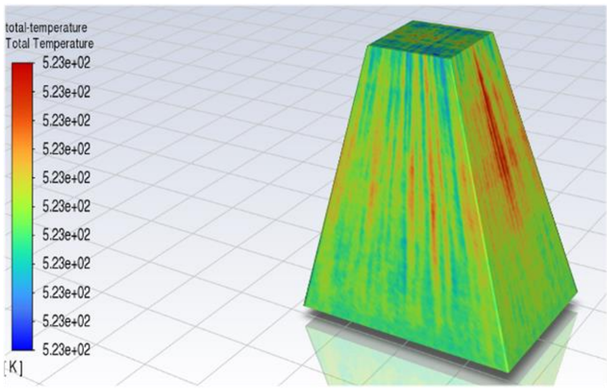


Fig. 15: Temperature Contours of the Chimney.

In the context of a trapezoidal chimney, the heat transfer and velocity characteristics are contingent upon several variables. These include the specific dimensions and geometry of the Chimney, the fluid flow conditions, and the properties of the transferred fluid. Heat transfer within a trapezoidal chimney is influenced by several factors, encompassing the Chimney's surface area, the thermal conductivity of the chimney material, and the temperature disparity between the fluid inside the Chimney and its surrounding environment. Figure 15 illustrates the temperature profile. If the chimney walls are constructed from a material with excellent thermal conductivity, such as metal, heat transfer through conduction from the hot gases within to the cooler surroundings is quite efficient. The maximum temperature attained within the Chimney is approximately 523 Kelvin.

6.1. Heat flux

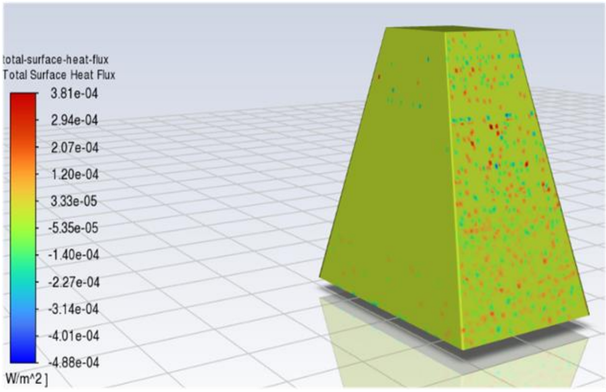


Fig. 16: Heat Flux Through the Chimney.

Heat flux, denoting the amount of heat transferred per unit area, is visually presented in Figure 16. It quantifies the heat energy transmitted across a specific surface over a defined time period. Heat flux is typically measured in units of power per unit area, such as watts per square meter (W/m²). Mathematically, it can be calculated using the formula:

$$q = Q / A \quad (11)$$

Where:

- q represents the heat flux (in watts per square meter, W/m²)
- Q is the heat transfer rate (in watts, W)
- A stands for the area through which heat is transferred (in square meters, m²)

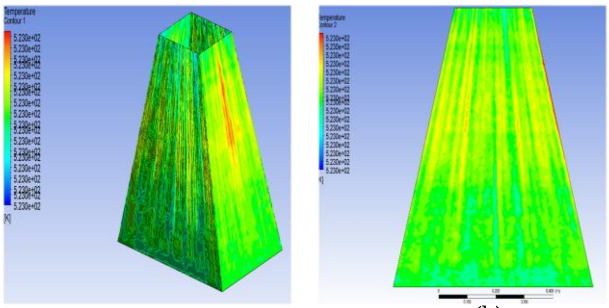
Therefore, the expression for Heat Flux (q), representing the rate of heat transfer per unit area, can be defined as:

$$q = -k * \nabla T \quad (12)$$

Where:

- q signifies the heat flux (in watts per square meter, W/m²)
- k denotes the thermal conductivity of the material (in watts per meter-kelvin, W/(m·K))
- ∇T represents the temperature gradient vector, which characterizes the spatial temperature variation (Kelvin per meter, K/m).

The maximum and minimum heat flux values are illustrated in the figure for reference.



(a) (b)

Fig. 17: (A) Temperature Contours of Chimney in Isometric Mode and (B) Temperature Contours of Chimney on A Plane That Is Passing Midway Through Chimney.

6.2. Post-processing values for temperature of chimney

Figures 17a and 17b vividly illustrate how the temperature across the surface of the Chimney varies, owing to the interplay of conduction and radiation. The red zone signifies the hotter temperature regions, while the green zone denotes areas with medium temperatures. The Chimney's unique frustum shape, where the passage area narrows towards the exit, plays a pivotal role in generating a substantial draught, aiding in effective ventilation.

6.3. Post-processing values for velocity of chimney

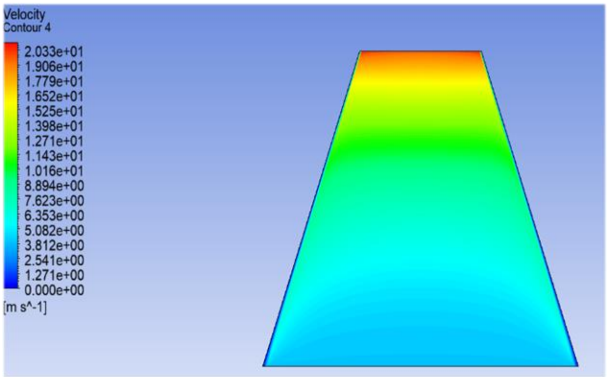


Fig. 18: Velocity Profile of Flue Gases Leaving from the Chimney.

The velocity profiles are illustrated in Figure 18. According to the continuity equation, velocity increases as the cross-sectional area decreases, as evident in Figure 18 where the red zone near the Chimney exit signifies higher velocity at that point. To calculate the velocity at the exit of a trapezoidal chimney, we apply the principle of conservation of mass, which dictates that the mass flow rate at the inlet must equal that at the outlet. Assuming steady flow, this principle can be expressed as:

$$A_1 * V_1 = A_2 * V_2 \qquad (13)$$

Where:

- A_1 = area of the inlet
- V_1 = velocity at the inlet
- A_2 = area of the outlet
- V_2 = velocity at the outlet

Given inlet dimensions of 76 cm * 43 cm and outlet dimensions of 23 cm * 27 cm, we convert these to square meters (m^2) for consistency: inlet dimensions become 0.76 m * 0.43 m, and outlet dimensions become 0.23 m * 0.27 m.

Rearranging the equation to solve for V_2: $V_2 = (A_1 * V_1) / A_2$

Substituting values: $V_2 = (0.76\text{ m} * 0.43\text{ m} * V_1) / (0.23\text{ m} * 0.27\text{ m})$

Simplifying further: $V_2 = (0.3268 * V_1) / 0.0621$

Therefore, the expression for the velocity at the exit of the trapezoidal Chimney is given as: $V_2 = 5.2632 * V_1$
Please note that this expression assumes incompressible flow, neglects frictional losses in the Chimney, and assumes that the Chimney's height doesn't impact the exit velocity.

6.4. Total energy and convection heat transfer coefficient vs height of chimney

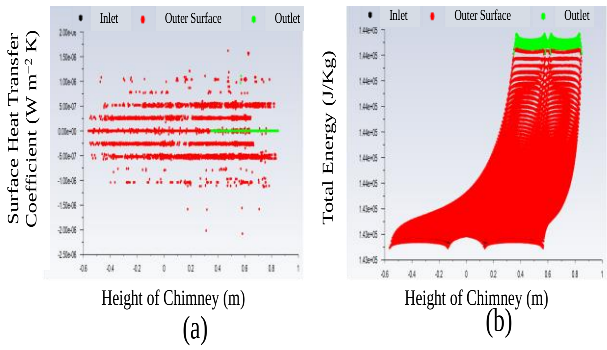


Fig. 19: Variation of (A) Convection Coefficient and (B) Total Energy of Chimney with Height of Chimney.

7. Conclusions

The new Tandoor design prioritizes ergonomics, eliminating the need for the Kandur to bend inside the Tandoor. Instead, bread can be installed without body contortion or exposure to hot gases. This improvement is made possible by introducing channels designed for bread placement. In contrast to the old design that generated significant indoor smoke, the new Tandoor boasts an efficient chimney design that prevents smoke from entering the shop. This crucial enhancement addresses health issues that previously affected people's well-being.
The old Tandoor design suffered from combustion issues due to inadequate vents, resulting in incomplete combustion and heavy smoke production. The new design incorporates numerous vents, facilitating complete combustion and reducing smoke generation. The efficiency of the old Tandoor stood at a thermal efficiency of 31%, whereas our innovative Tandoor design has substantially increased thermal efficiency to an impressive 80%. Temperature measurements for the new Tandoor were validated against Ansys Fluent. Ten temperatures for the channel, Chimney, flue gases, and outer wall were measured using K-type thermocouples and an Infrared camera. The resulting average temperature values were 220.2°C, 83.6°C, 160.9°C, and 28.8°C, respectively. The redesigned Tandoor excels in ergonomics and significantly enhances bread production capacity. It successfully addresses various health concerns, such as back strain and chest problems,

which were prevalent in the previous design. Furthermore, this innovative Tandoor ensures complete fuel combustion, resulting in minimal smoke emission from the Chimney. The enhanced ergonomics of the new Tandoor make it more user-friendly, reducing the physical strain on operators and providing a more comfortable working environment. Moreover, the improved design leads to increased bread output, which is crucial for meeting higher demand and improving overall productivity. Health issues related to back strain and chest problems have been effectively mitigated through thoughtful design modifications, prioritizing the well-being of workers and ensuring a healthier workplace. The comprehensive combustion process in the new Tandoor also contributes to a cleaner environment by significantly reducing smoke emissions, making it a more environmentally friendly and sustainable option.

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