Evaluation of Brick Kiln Performances using Computational Fluid Dynamics (CFD)

A thesis submitted in fulfillment of the requirements for the degree of Master of Engineering

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part to qualify for an academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Abstract

Modern history of civilization is concurrent to the use of brick and its manufacturing. Brick kiln is the most important component in the manufacturing of clay-burnt bricks. Poorly operated brick kilns are considered as the major sources of greenhouse gas (GHG) emission nowadays. Various types of brick kilns are in operation throughout the world. Tunnel kiln is the most widely used technology in developed countries as it is highly automated. Other technologies which are quite popular in developing countries are: Hoffman kiln, Vertical Shaft kiln, Fixed Chimney kiln, Zigzag kiln, etc.

Computational Fluid Dynamics (CFD) software, ANSYS CFX is being applied to evaluate performance of Tunnel kiln using natural gas as its fuel. The idea of a typical Tunnel kiln layout geometry has been envisaged from local brick industries. The length, width and height of the Tunnel kiln geometry are taken as 100 m × 3.24 m × 1.48 m. The length and width of the brick stack is taken as 920 mm × 440 mm. With a gap of 400 mm and 100 mm between two brick stacks longitudinally and laterally respectively, a total of 450 (6 × 75) stacks can be accommodated inside the kiln at a time. Brick stack height including the kiln car height is taken as 1.38 m. There is a clearance of 100 mm between the stack and the kiln roof. To produce certain quality bricks/ceramics, a particular temperature distribution throughout the kiln needs to be maintained. This temperature distribution with respect to the kiln length is known as Tunnel kiln curve. To achieve the Tunnel kiln curve obtained from industry for ordinary brick type, some design parameters need to be optimized for a given geometry. Selection of these optimized design parameters are obtained through a series of trial and error runs of the CFD model. The total length of the tunnel can be divided into pre-heating, firing and cooling zones. Green bricks pass through the pre-heating, then firing and finally the cooling zones, while fresh air flows in opposite direction of the brick stack move. It is to be noted that brick industries are very reluctant to disclose any of those technical secrets related to their brick kiln design. In this regard, this design is based on initial guesses of those parameters and slowly come up with best performing scenario with respect to considered Tunnel kiln curve.

To achieve the Tunnel kiln curve, the design parameters that need to be played around are gas and air flow rates, flow directions, their inlet-outlet number, spacing and placements at different locations of the kiln are considered very crucial. Other important parameters that are varied include brick stack placement with respect to air and gas inlet-outlets, gaps between
kiln roof and stacks and gaps between two consecutive stacks. To supply adequate air, a large rectangular air inlet with an area of 0.8 m$^2$ is placed at the roof of the exit end of the kiln. To maintain the air temperature distribution as given in Tunnel kiln curve, one intermediate size air outlet with an area of 0.4 m$^2$ and a series of 13 rows × 12 columns small air inlet-outlets (openings) are also placed at the roof of the kiln in the cooling zone. All these heated air has been transferred to dryer to dry the green bricks. A series of 12 rows × 12 columns of gas inlets are placed in the roof of the firing zone. At the entry end of the tunnel, a flue gas outlet with an area of 0.8 m$^2$ is placed in the roof.

Due to three dimensional nature of the kiln geometry, the CFD simulation of the whole system would be very time consuming. A close look of the geometry dictates that, a one-sixth slit of the total geometry (100 m × $\frac{1}{6}$×3.24 m) containing 1 row × 75 stacks of bricks is enough to simulate the whole geometry of the kiln. This modelled geometry is meshed and mesh independency is checked using ANSYS Mesh. Turbulence, combustion and radiation models are adopted to simulate a realistic Tunnel kiln environment using ANSYS CFX Pre. Several model runs are performed until the simulated temperature distributions obtained closely replicate the Tunnel kiln curve of the industry. From these simulations, the optimum Tunnel kiln design is suggested. The resulting CO$_2$ and NO emissions are also obtained from these simulations. Gas inlet velocity is proposed to be 6 m/s with an inlet diameter of 25 mm. Gas velocity direction is suggested to be normal to the kiln roof. Air flow direction should be at 14° with kiln roof towards firing zone. Gaps between brick stacks and the kiln roof should be about 200 mm. To get a uniform distribution of heated gases, positions of the brick stacks are such that on each occasion of its changed position it would be just directly below the inlet jets. Gaps between two consecutive brick stacks should also be reduced to 200 mm instead of the initially assumed 400 mm spacing. Hence additional number of bricks could be accommodated inside the kiln at a time which will result higher production of bricks with the same amount of fuel.
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Nomenclatures

$A_i$ = face normal vector

$f_i$ = vector from the centroid of the cell to the centroid of that face

$e_i$ = vector from the centroid of the face to the centroid of the edge

$\Theta_e$ = equiangular face/cell (60 for tets and tris, and 90 for quads and hexas)

$\Theta_{\text{max}}, \Theta_{\text{min}}$ = maximum and minimum angles between any two edges of the cell

$\Theta_e$ = angle between any two edges of an ideal equilateral cell with the same number of edges

$n$ = ip-face normal vector

$s$ = node to node vector

$\rho$ = density

$\vec{v}$ = velocity

$S_m$ = source term

$p$ = static pressure (Pa)

$\tau$ = stress tensor

$\vec{F}$ = external body forces

$\vec{g}$ = gravity

$t$ = time

$E$ = energy term

$\rho$ = density

$k_{\text{eff}}$ = effective turbulent kinetic energy

$T$ = local temperature in Kelvin

$h$ = enthalpy for ideal gas

$J$ = diffusion flux

$\tau_{\text{eff}}$ = effective stress tensor

$S_h$ = volumetric heat source term

$I$ = radiation intensity
\( \vec{r} \) = position vector

\( \vec{s} \) = direction vector

\( \vec{s} \) = scattering direction vector

\( \alpha \) = absorption coefficient

\( \sigma \) = Stefan-Boltzmann constant

\( n \) = coefficient of excess of air

\( T \) = local temperature in Kelvin

\( \sigma_s \) = scattering coefficient

\( \phi \) = phase function

\( \Omega \) = solid angle

\( G \) = incident radiation

\( C \) = linear anisotropic phase function coefficient

\( h_c \) = wall heat transfer coefficient

\( q_w \) = total heat flux into the domain by convective and radiative processes

\( \rho_m \) = mixture density

\( \vec{v}_m \) = velocity

\( \mu_t \) = turbulent viscosity

\( G_{k,m} \) = production of turbulence kinetic energy

\( G_b \) = production of turbulence kinetic energy because of buoyancy

\( k \) = turbulent kinetic energy

\( \epsilon \) = turbulent dissipation rate

\( C \) = linear anisotropic phase function co-efficient

\( \sigma_k \), \( \sigma_\epsilon \) = scattering coefficient for \( k \) and \( \epsilon \)

\( E \) = emission of CO\(_2\) in tCO\(_2\)e

\( SFC \) = specific fuel (energy) consumption in the kiln (TJ/brick)

\( Q \) = total number of brick production

\( EF \) = IPCC default carbon emission factor for the given fuel

\( CF \) = carbon to CO\(_2\) conversion factor
\( Q_{\text{coal}} \) = total coal consumption per 100,000 bricks for the given kiln

\( CV_{\text{coal}} \) = calorific value of the coal (16,748 KJ/kg coal)

\( Q_{\text{bricks}} \) = number of bricks produced
Chapter 1
Introduction

1.1 Background

Brick and its manufacturing have a major contribution for the development of modern civilization. Currently there are about 125 billion bricks produced annually using automated kilns, which are about 10% of the total production worldwide (Habla Zigzag kilns 2011). While the processes of preparing green bricks vary widely, the burning of these green bricks need efficient kiln/burner. Here, kiln is the whole setup for burning bricks comprising preheating, firing and cooling zones whereas burner is the portion where firing occurs. These kilns are one of the most polluting sources of greenhouse gases in the atmosphere. There are many types of brick kilns available in the market. Commonly available technologies are like Tunnel, Habla Zigzag, Vertical Shaft, Hoffman and Fixed Chimney kilns. Among these technologies, gas fuelled Tunnel kiln is mostly used in developed countries while other semi-automated to manually operated technologies are visible in developing countries. Both coal and gas are the two most commonly used fuel types in these kilns/burners.

Use of technology in brick burning sector primarily started from ‘Clamp kiln’ which is the oldest form of brick burning method invented thousands of years ago and now almost obsolete. Eventually newer forms of technologies including Bulls Trench kiln (which is quite similar to Fixed chimney kiln but with movable chimney) and others gradually being adopted. At present, the brick industries in developing countries are still using by and large coal-based labour-intensive technologies such as, Hoffman, Vertical Shaft and Habla Zigzag (Habla Zigzag kiln 2011). Gas fuelled Tunnel kiln got the edge in developed countries as it is highly automated and labour cost in these countries are quite high. This research is going to provide an idea about the different brick kiln technologies in use throughout the world.

Due to technological advancement, leading brick companies in Australia and other parts of the developed world are replacing their age old tunnel kilns by new efficient burners and its accessories (Energy Efficiency Opportunities 2007). These burners are making controlled burning of fuel for high performance and reduced emission of greenhouse gases. One of the
major activities of brick manufacturing is the combustion of fuel and as a result huge pollution is emitting into the atmosphere (Environment Protection Authority 1998).

Computational Fluid Dynamics (CFD) is a computer-based simulation tool, nowadays used for analysing the behaviour of systems involving fluid flow, heat transfer, and other related physical processes. Simulation using Computational Fluid Dynamics (CFD) is a relatively novel concept for design optimization and to comprehend combustion processes inside the kiln, especially in the brick manufacturing sector.

There are limited researches where CFD simulation was conducted to find out performances of a Tunnel kiln (Hauck 2005). It is found that even fewer of these researches focused on emission performances (Chacon et al. 2007). In other works (Energy Efficiency Opportunities 2007, NICE 2001), the efficiency of the existing burners are attempted to be improved by modification in few auxiliary components. Garcia et al. (2006), Meng (2011), and NICE (2001) concentrated researches on brick stack height, brick placement, gap between bricks, solid-solid recuperation, etc. However, most of these studies are conducted on industrial commitment, so detailed methodology and outcomes are not available. As Tunnel kiln is the most widely practiced technology in developed countries, CFD simulation of this technology is going to give an insight of this technology.

It is found that efficient combustion of fuel is largely related to proper supply of air and fuel inside the kiln as well as the geometry and design of the kiln. As such it is envisaged that the use of Computational Fluid Dynamics (CFD) is going to facilitate the simulation of optimum design parameters of the Tunnel kiln and at the same time the amount of pollution, CO\textsubscript{x}, NO\textsubscript{x} emissions in the combustion. Literature review (Durakovic et al. 2006, Oba et al. 2011, Atanasov et al. 2007) and field visit to few local industries revealed that different levels of temperature are required inside the Tunnel kiln along its distance, for effective combustion of bricks. This plot of temperature vs. distance is called the ‘Tunnel kiln curve’, an essential standard that needs to be maintained to obtain a particular quality brick. Different quality bricks like, ordinary, ceramics, refractory, porcelain and many other variants, each has its own characteristic temperature curves to be maintained during combustion in the Tunnel kiln in order to obtain the required quality produce. Application of CFD for given field condition and geometry could simulate the appropriate gas and air inflow rates, emission outflow rates and progress of combustion until the
Tunnel kiln curve temperature vs. distance is more-or-less achieved. It should be mentioned here that no company in the market is willing to give their specific information and data because of their trade confidentiality unless otherwise research commissioned by themselves. They even do not permit to take any photograph inside the brick manufacturing compound. Their own research findings are also classified and thus very little information available in the literature.

The most commonly used CFD software, ANSYS is used to evaluate the combustion and emission performances of the commercially available Tunnel brick kiln using gas as its fuel. This study is going to give better understanding about the simulation of combustion using gas in the kiln. CO$_x$ and NO$_x$ emission is also going to be simulated. Design of the kiln is optimized to provide better combustion efficiency and thereby to reduce emission.

1.2 Objectives

The main objective of this research is to optimize the design of the Tunnel kiln for efficient fuel usage. To achieve that, the temperature distribution from the simulation needs be matched with the desired Tunnel kiln curve found in industry. This objective can be achieved by CFD simulation where temperature, velocity and emission distributions inside the Tunnel kiln can be obtained. Generated temperature distribution can be matched with the industrial curve and by interpreting the curve, efficient design can be suggested.

As such the two specific objectives of this research are as follows:

1. To ensure close maintenance of temperature vs. distance of the Tunnel kiln curve for a given quality brick production and thereby optimize the design of the Tunnel kiln in relation to gas and air supply rates and its supply spacing, emission outflow rates and its spacing, and other geometrical features like brick stack placement and its gaps inside the kiln.

2. To identify the emission performance of different design in Tunnel kiln to suggest the environment friendly one.
1.3 Expected Deliverables

An optimised design of Tunnel kiln can be obtained by matching with an industrial Tunnel kiln curve to ensure the most efficient fuel use and reduction of emission.

1.4 Scope

**CFD simulation on Tunnel kiln**

The geometry of the object, where fluid flow and combustion processes are to be simulated, should be defined first. As such the Tunnel kiln geometry/settings in question is drawn using CFX Design Modeller of the ANSYS. Standard/typical dimensions of the kiln are collected from industrial sources. Air inlet and outlet, burner placement and brick stack placement is defined accordingly. CFD does not consider solid body parts during simulation, so brick stacks are defined as heat absorbing walls. Only fluid body domain is taken into consideration for flow analysis. Geometric configurations is drawn for fuel type - gas. Inlet and outlet air temperatures and mass flow rates, burner temperature and other properties along with fuel flow rates are defined. Gas combustion reactions are given as input using ANSYS library of reactions.

ANSYS Mesh is used to generate appropriate meshes and its quality checking. CO\textsubscript{x} and NO\textsubscript{x} emissions from the brick kiln are simulated. Simulation results are compared with the findings from field and desk studies.

1.5 Thesis Outline

This thesis consists of 6 chapters.

Chapter 1 presents the background of the brick sector, problems in this sector, research objective, expected deliverables and research scope.

Chapter 2 provides a basic understanding of bricks manufacturing and its raw material. The chapter explains brick production stages, firing process and brick kiln technologies worldwide. This chapter also gives a brief overview of Computational Fluid Dynamics (CFD) and its simulation steps. It also identifies the importance of using CFD in brick kilns.
Chapter 3 describes how to use CFD simulation using ANSYS CFX., how to draw the geometry, perform meshing, check mesh quality, run models for heat transfer, combustion, radiation and turbulence etc.

Chapter 4 presents simulation of Tunnel kiln and its design optimization. It also describes how the geometry is selected, CFD model is built, what are the boundary conditions etc. Simulation results along with how the design is optimized and emission performance improved is analysed.

Chapter 5 presents the conclusion of the study and recommendation for future work in the brick kiln technology.
Chapter 2
Literature Review

2.1 Introduction

2.1.1 Bricks as building block
Brick products are widely used in construction and manufacturing industries. Bricks were first produced in a sun-dried form at least 6,000 years ago. Bricks were also the chief building material in the ancient civilization. Clay, the basic ingredient of brick, is mined from open pits, molded, and then fired in a kiln to produce strength, hardness, and heat resistance to form bricks.

A brick is a block, or a single unit of a ceramic material used in masonry construction. Typically bricks are stacked together, or laid. Cement is used to hold it together and make a permanent structure. Bricks are typically produced in bulk quantities. It is regarded as one of the longest lasting and strongest building materials used throughout history. Brick is considered as a weight bearing building unit, typically laid horizontally. Usually it has a standard size and shape, however this standard size and shape varies according to different countries.

Bricks are made from dried earth, usually from clay. In some cases, it is merely dried. More commonly it is fired in a kiln of some sort to form a true ceramic. Bricks can also be made from lime-and-sand, concrete, or shaped stone. Bricks can be classified in many groups.

2.1.2 Clay as a building material
Clay, wood and stone is some of the oldest building materials on Earth. More than half of the world's population live or work in a building made with clay. From ancient times clay is an essential part of the load-bearing structure.

Components of clay material
Common clay minerals are hydrated aluminum silicates that are usually found from the weathering of rocks. Most clay mineral lattices have two structural units. ‘Silica sheet’ is one such unit formed by tetrahedron tetrahedral consisting of a Si$^{4+}$ surrounded by four oxygen octahedral, and an Al$^{3+}$ ion is surrounded by six hydroxyl groups. These octahedral sheets combine with silica sheets to form the clay minerals (Meng 2011).
Some of the most important clay minerals are kaolinite, Al$_2$O$_3$.2SiO$_2$.2H$_2$O, bentonite, Al$_2$O$_3$.4SiO$_2$.5H$_2$O, montmorillonite, Al$_2$O$_3$.4SiO$_2$.H$_2$O, halloysite, Al$_2$O$_3$.SiO$_2$.3H$_2$O and illite, K$_2$O.3Al$_2$O$_3$.6SiO$_2$.2H$_2$O (Wikipedia 2011). Combinations of clay minerals with metal oxides and organic matter is called clay. Geologic clay deposits are mostly composed of phyllosilicate minerals containing variable amounts of water trapped in the mineral structure (Wikipedia 2011). Various types of clay minerals can form various types of bricks or pottery items based on their characteristics. Clay characteristics may even affect the quality of the bricks.

**Formation**

When there is a gradual chemical weathering of rocks for a long period of time, clay minerals are formed. There are other processes of forming clay minerals such as hydrothermal activity. Clay deposits may be formed in a place as residual deposits of soil. Thick clay deposits usually are formed as the result of a secondary sedimentary deposition process after they have been eroded and transported from their original location of formation.

Primary clays, also known as kaolin, are located at the site of formation. Secondary clay deposits move by erosion from their primary location. Clays are distinguished from other fine-grained soils by differences in size and mineralogy. Silts are fine-grained soils usually having larger particles in size compared to clay and it does not include clay minerals. However some particle sizes and other physical properties are common in both clay and silt. There are many naturally occurring deposits which include silt and also clay. The distinction between silt and clay depends on particle size or the plasticity properties of the soil.

**Grouping**

There are quite a few main groups of clays including kaolinite, montmorillonite-smectite, illite, and chlorite. Though there are different types of pure clays, however "natural" clays are usually mixtures of these groups along with other weathered minerals. When clay is mixed with water it shows plasticity to some extent. Drying clay makes it firm and when clay is fired inside a kiln, permanent physical and chemical changes occur. These physical and chemical changes convert clay into ceramic material. Because of these properties, clay is used for making both utilitarian and decorative pottery items. Different types of clay, when used with different minerals and firing conditions, are used to produce earthenware, stoneware, and porcelain.
Clay is first shaped and then fired to form ceramic. Clay is also used in many industrial processes, such as paper making, cement production, and chemical filtering. Clay is relatively impermeable to water, so it is used as natural sealing.

2.2 Brick Production

The main steps in the manufacturing of brick/ceramic products are largely reliant on the materials used and the final product. Figure 2.1 schematically shows the typical process and necessary raw material supply and disposal facilities. This process is made up of the following steps: mining/extraction of clay and transport to the plant, storage of the raw materials, moulding and shaping of green bricks, drying, firing in brick kiln and cooling of finished product.

Firing process

Firing is a key process in the production of bricks, as it controls many important properties of the finished products. These include mechanical strength, abrasion resistance and dimensional stability, resistance to water and chemicals, and fire resistance.

When the clay-based ceramic products are fired in a kiln, all moisture is driven off at temperatures between 70°C and 200°C. If organic matter and iron pyrites are present, oxidation
takes place at temperatures between 300°C and 500°C. Water combined within the structure of clay minerals (‘crystal water’) is usually released at temperatures between 500°C and 650°C, whilst carbonates such as calcite and dolomite dissociate with the release of carbon-di-oxide in the temperature range between 750°C and 950°C.

\[ \text{CaMg(CO}_3\text{)}_2 \rightarrow \text{CaO} + \text{MgO} + 2\text{CO}_2 \quad \text{and} \quad \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \]

The most important changes relating to the development of ceramic properties involve the breakdown of the lattice structure of the original clay minerals, followed by the formation of new crystalline compounds and glassy phases. It is found that the temperature at which vitrification (glass formation) takes place varies according to the mineralogy of the clay. Vitrification usually commences at about 750°C and is completed by about 1050°C (for many brick clay) or about 1150°C in the case of more refractory fireclays (Meng 2011).

Firing temperature of different types of bricks and ceramics are given below (Meng 2011):

- **Earth ware**: 1000-1150°C
- **Facing bricks and clinkers**: 1000-1200°C
- **Silica bricks**: 1450-1550°C
- **Vitreous china**: 1200-1300°C
- **High alumina bricks**: 1500-1800°C
- **Basic bricks**: 1400-1800°C
- **Clay blocks**: 880-1020°C
- **Wall and floor tiles**: 1080-1300°C
- **Pottery ware**: 750-950°C
- **Stoneware**: 1130-1280°C
- **Porcelain**: 1300-1450°C
- **Roof tiles**: 1000-1150°C
- **Fireclay bricks**: 1250-1500°C
2.3 Factory Setup

A typical factory setup is shown below. The length and width of the factory varies largely based on the kiln size and production capacity. However in all brick factories, green brick preparation and finished product area take larger area than the actual kiln size.

Raw materials for bricks need to be collected from various sources. Based on the availability of the raw material, the storage capacity needs to be determined. If it is available throughout the year then too much raw material piling is not necessary. However, if the supply of raw material is low then bulk quantity of raw material needs to be collected whenever available. Then it needs to be stacked for year round production. Availability of raw material depends of the location of the brick kiln.

Molding green bricks requires quite a lot of space if it is achieved manually. However, in most developed countries the whole process is automated and does not need much space. In developing countries, as there is significant manual labor involved with this process, so it requires a large space in the factory.

Bricks can be dried using waste heat from the kiln or it can be sun-dried. Developing countries use sun drying as it requires significant cost to set up artificial dryer. Brick production is a continuous process and cannot be increased or decreased based on the production. Fire once lit, runs indefinite time, so a significant space is needed for stacking the finished product.

Figure 2.2: Brick factory layout
2.4 Kiln Types

The range of kiln types for brick/ceramic production from ancient times to now is very large. If it is investigated more in depth, not only do the kiln types differ, but there are also many variants within each kiln type exist. If the classification of the kiln type in the present literature is investigated, the chronological facts about the development of the kiln can be observed.

Generally there are two basic types of kilns to produce ceramics: periodic kilns and continuous kilns. In periodic kilns, bricks were loaded, sealed, heated, cooled and unloaded for every firing. In continuous kilns, once the fire is lit, it continues until deliberately stops. Either brick moves through the firing zone or the fire travels through the kiln as the fuel inlet position changes. Within these classifications there are many sub-classes for each type exist. While it is impossible to enumerate all types of kilns, some most important kilns are discussed to give ideas about its technical and operational principles and thus to understand the selection options.

Popular brick kiln technologies worldwide include Fixed Chimney kiln (FCK), Hoffman kiln, Habla Zigzag, Vertical Shaft Brick kiln (VSBK) and Tunnel kiln. Other than Tunnel kiln all other four types of technologies still are in operation in developing countries. In this section a comparative analysis is provided between these technologies practiced in the developing countries. A brief description of different types of brick kilns that are available in developing and developed countries are given in the following sub-sections.

2.4.1 Fixed Chimney kiln (FCK)

FCK is rectangular in shape and measures around 80 m long and 20 m wide. FCK is a modified version of the previously used Bull’s Trench Kiln (BTK) which had a low-height movable metallic chimney. BTK was more polluting than the present FCK as the chimney height was considerably low. FCK is usually constructed on low lying ground, sometimes partially under the ground. The tall fixed chimneys as shown in Figure 2.3 of these kilns create a strong draft and release flue gas at a height of 40 m above the ground, providing faster and better dispersion than previous low height chimneys of BTKs. FCKs are integrated with underground pipes/ducts to collect flue gases from anywhere in the kiln to the fixed chimney. The width of the fixed chimney is selected in such a predefined way to accommodate all the flue gas collecting ducts. The cost of constructing the chimney is nearly 50% of the total cost of the kiln (Clean Energy...
Alternatives 2011). Green bricks are stacked at one end which is known as the preheating zone and fired bricks are taken out from the other end which is known as the cooling zone. Fuel (coal) is charged from the top in between these two zones which is known as the firing zone.

The burning of coal in FCK is not efficient by any means. Thick black smoke emits from the chimney due to inefficient manual coal charging. Between two coal charging, flue gas color changes from grayish black to milky white and remains white until the next coal is charged. So the pollutants visible are actually fly ash and un-burnt carbon particles. Existence of un-burnt carbon particles in the flue gas results from excess coal charging compared to air supply to complete the combustion in the firing zone. Light fine coal particles become airborne to escape from the firing zone and reach the pre-heating zone (colder) where it is impossible to get burnt. Larger coal particles get deposited on stacked bricks, where it slowly burns out to leave ash on the brick surfaces. Expert firemen are essential for effective control of combustion. A frequent changing of smaller quantity coal is better for consistent burning, which in turn releases a much less pollution into the atmosphere. Also, high quality coal is essential to release less pollution.

Figure 2.3: Fixed Chimney kiln (FCK)
Figure 2.4: Few operational FCKs near Dhaka, Bangladesh

Figure 2.4 shows few operational FCKs in Bangladesh. The black smoke pouring out of it indicates incomplete combustion, which is a major source of greenhouse gas emission in Bangladesh. Figure 2.5 shows the coal charging process in a typical FCK.

Figure 2.5: Workers pouring fuel (coal) for combustion inside a FCK
2.4.2 Habla Zigzag kiln

Habla Zigzag kiln has some similarity with FCK. It is rectangular in shape and measures 80 m by 25 m (CDM 2007) as shown in Figure 2.6. It has an 18 m high fixed chimney located on one side of the kiln. A typical Habla Zigzag kiln is shown in Figure 2.7. At the bottom of the chimney there is a blower, which draws flue gas from the kiln and discharges into the atmosphere. This kiln is divided into 20 to 40 chambers by green brick stacks, which are separated from each other in such a way that the hot gases move in a zigzag path through the kiln (Maithel et al. 1999). So the length of airflow inside the kiln is increased by zigzagging the chambers. Likewise fire follows a zigzag path instead of the straight path practiced in BTK or FCK. In the long travel path of the hot gas, the green bricks absorb much of the waste heat to have better drying and moisture reduction. Based on various studies, Zigzag Kiln is considered to be 10-15% more fuel-efficient than the FCK (Clean Energy Alternatives 2011).

Figure 2.6: Schematic view of a Habla Zigzag kiln
The repeated changes of flue gas direction and impacts on the walls and green brick stacks, lead to the deposition of significant amount of particles and carbons on the floor. This is the reason why Zigzag kiln produces less emission than FCK. Zigzag also incorporates flue gas scrubber, where the connecting duct between the center of the kiln and the inlet of the draft fan is half to two-third full with water. Flue gas impinges on water to lose some of its particulates further.

Zigzag kiln construction cost is approximately the same as that of FCK (Clean Energy Alternatives 2011). As this technology is quite similar to FCK and the conversion expenditure is relatively low. Qualitative evaluation on poorly managed Zigzag kilns indicate that these are as polluting as the FCKs, while the better managed kilns produce about half of the FCKs pollution (World Bank 2011). An improved Zigzag kiln with a standard design leads to lower emission and increased energy efficiency (Habla Zigzag kiln 2011). It includes improvements such as use of internal fuel by mixing pulverized coal into the clay to form green bricks, better insulation...
with reduced heat loss and better flue gas scrubber. The use of internal fuel can rise up to 80% of the total fuel requirement, while the remaining 20% is destined to produce much less emission. The current FCKs can also be converted into Zigzags by retaining FCK’s tall chimney in place (BUET 2007; Feedback Ventures 2010).

### 2.4.3 Hoffman kiln

Hoffman is a gas-fired kiln, has quite similar construction and operation procedure as that of FCK. The significant difference is - it has a fixed roof as shown in Figure 2.8, whereas FCK has a temporary roof. Due to this fixed roof, bricks can be fired throughout the year in Hoffman kiln. A typical Hoffman kiln is around 100-130 m by 20 m (CDM 2007). Although this kiln should run throughout the year, in practice, during monsoon the number of bricks produced decreases significantly due to rainfall. Increased humidity and absence of adequate sunlight also contributes to this decreased production. Often manufacturers tend to overproduce bricks to sell during the rainy season, raising the requirement of adequate storage facility to stock large number of finished bricks. In countries where there are long rainy season occurs, not only bricks but also raw materials including clay have to be stored.

![Figure 2.8: Schematic view of a Hoffman kiln (Kynaston 1984)](image)
Because of the thick wall and effective insulation, heat loss becomes minimized to its surrounding. The brick stacking technique is similar as that of FCK as shown in Figure 2.9. Pipe type burners are inserted from the top to supply fuel (natural gas) to the combustion chamber where bricks are burnt. Burners are shifted forward through holes at the top of the kiln when burning of a particular batch is complete. Fired bricks are unloaded from one end and green bricks are stacked to the front.

Controlling the fire is the trickiest part of the whole operation. In most of the kilns there is no fire controlling instrument. So the fire master based on his experience changes gas flow rate and alters opening and closing of dampers, located at selected points of flue gas network, to control fire. Several years on job training is required for a person to become a master of fire.

In Hoffman brick kiln, gas is used as fuel. Usually gas fired kilns provide better colored bricks. In developing countries, there is a wrong perception that bricks with bright color are strong. However, quality of bricks can only be determined by their compressive strength and water absorption capacity.

![Figure 2.9: Stacking of green bricks inside Hoffman kiln](image)

**Coal based Hoffman kiln**

Hoffman kiln also uses coal instead of gas as fuel as shown in Figure 2.10. Some modification is done in kiln design by diverting flue gas through green bricks before stacking those inside the kiln. Countries with lacking or inadequate gas, people prefer coal based kiln over gas based kiln.
However coal based Hoffman kiln generates more pollution than gas based one (IIDFC 2009). Useful life of this type of kiln, with proper annual maintenance, is at least 10 years (Clean Energy Alternatives 2011).

![Image of workers pouring pulverised coal](image.png)

**Figure 2.10:** Workers pouring pulverised coal for combustion through holes at the roof

### 2.4.4 Vertical Shaft Brick kiln (VSBK)

Vertical Shaft Brick kiln (VSBK) was first developed in China and is very popular in rural areas for small-scale production. In addition, the kiln is simple to construct and operate round the year, making it ideal for rural areas. It showed limited success in India and Nepal. Compared to FCK, VSBK uses less energy and emits less pollution (DA - PA 2010). However, brick quality of VSBK is relatively poor compared to its incremental investment.

In VSBK, there is a vertical shaft of rectangular or square cross-section, as shown in Figure 2.11. Green bricks are loaded in batches from the top. Bricks move down the shaft as it goes through preheating, firing and cooling zones and finally unloaded at the bottom. Combustion of fuel (coal) takes place in the middle of the shaft. Air enters at the bottom and flows through the burnt bricks, cools it and then passes through the combustion zone at the middle where it reacts with coal and finally releases some of its energy obtained in the combustion zone by preheating green bricks. So, counter current heat exchange occurs inside the kiln.
Figure 2.11: Schematic view of a VSBK

Figure 2.12: A typical VSBK in Bangladesh
Unlike FCK, VSBK has a permanent structure and can produce bricks throughout the year. It has a design life of 8 to 10 years with minimum maintenance requirement (Practical Action 2010). The greatest benefit of VSBK is, as the kiln constructed vertically, it is very economical in utilizing space. In VSBK, pulverized coal up to 50% of the total fuel demand can be mixed with clay as internal fuel. The rest of the coal is charged along with the green bricks in the loading process. The charged coal that enters the firing zone slowly tends to burn completely and thus providing a higher efficiency and less pollution. This is a contrast in comparison to other coal-fired kilns, where coal is charged in a regular interval. Operation of VSBK requires more skilled labor. Brick unloading can be a challenge because bricks tend to crack if withdrawn quickly from the hot kiln. However, VSBK bricks satisfy typical standard related to compressive strength and water absorbency despite its dull color compared to FCK bricks. A typical operating VSBK is shown in Figure 2.12.

### 2.4.5 Tunnel kiln

Tunnel kilns are widely used in brick and particularly in ceramic manufacturing industries. It is an elongated kiln, which looks like a tunnel and is made of refractory and heat insulated construction material. Inside the kiln, kiln cars transport the green wares and eventually the final products. It has typical length between 35 m and 250 m, width between 1 m and 6 m and height between 1 m and 2 m (Oba et al. 2011).
Tunnel kilns are continuously operated kilns that receive bricks on track-mounted cars called kiln cars. These cars are fed into the kiln, one after another, and are pulled through the kiln’s different drying and firing zones. In Tunnel kiln, green bricks are exposed to a sequence of heat treatment cycles, moving slowly through various temperature zones over the kiln cars. These cars are put on the tracks and enter the drying portion of the kiln in separate chamber where they remain for about 48 hours to reduce the moisture content. Preheated green wares then enters into the kiln from one end of the kiln, increase in temperature and undergoing of the sintering. During sintering the atoms in the green brick diffuse across the boundaries of the particles, fusing the particles together and creating one solid piece. The green wares become products and move out of the kiln from the other end. In the firing zone of the kiln, the temperature is usually between 850°C and 1250°C which needs to vary with the type of brick. In the preheating and firing zones, the heat from the high temperature flue gas preheats the green ware. Therefore the green ware temperature increases and the flue gas temperature decreases. After the removal of all the products the empty kiln car is going to the other side of the kiln, to begin the next production cycle. Usually 40 to 80 kiln cars remain at a time inside the Tunnel kiln (Yu 2007). To complete a full cycle of brick burning inside the Tunnel kiln it requires 36 to 72 hours to achieve different quality bricks and ceramics.

The traditional Tunnel kiln suffers from long production cycle, high energy intensity, relatively high rejection rates (~10%), and low levels of automation – in many phases of the traditional process, bricks are moved and stacked manually. However, Tunnel kiln is the most modern brick kiln, has scope for high automation. Both coal and gas can be used as fuel. Though it produces the best quality bricks but the cost is higher compared to other brick kilns. Since 1947, Tunnel kilns are gradually replacing circular intermittent kilns. In recent years, Tunnel kiln has become the most popular and commonly used kiln in developed countries as this kiln is highly automated and requires less manpower.

The layout of a typical Tunnel kiln is shown in Figure 2.13, where the three temperature zones as shown are: preheating, firing and cooling. The solid and gas temperature profile and flow direction are also shown in the figure.
2.4.6 Comparative overview of different brick kiln technologies

This section compares different aspects of brick production from collecting raw materials to making finished product of Fixed Chimney Kiln (FCK), Zigzag kiln, Coal based Hoffmann kiln (HK) and Vertical Shaft Brick kiln (VSBK) are described in the following paragraphs.

**Land requirement:** Land requirement for a FCK or a Zigzag is about 3-4 acres whereas that for a coal based Hoffmann Kiln (HK) is about 12 acres (CDM 2009). Higher land requirement for coal based HK also ensures greater production capacity. Major part of the land requirement is needed for brick molding, drying and other brick processing operations. If only the kiln portion is compared then the land requirement for coal based HK is less than half compared to FCK. For VSBK, land requirement is less than one-fourth of FCK for same amount of production (Practical Action 2010). The high variation of cost for different category lands has made this a vital issue for entrepreneurs for selecting the type of kiln.

**Fuel requirement:** Coal is the only option for brick industries in countries where natural gas is low in supply. Those previously constructed Hoffman kilns are barely using natural gas as fuel and the consumption rate is 15,000-17,000 m$^3$ per 100,000 bricks (Clean Energy Alternative 2011). Considering energy consumption requirement, coal based HK is more efficient than FCKs and Zigzag kilns. The coal requirement for FCK is around 24 ton per 100,000 brick production (World Bank 2011). Zigzag kiln and coal based HK consume around 18 and 14 ton coal per 100,000 brick production, respectively (CDM 2007). VSBK is the most fuel-efficient, consuming least fuel around 10 ton of coal for 100,000 bricks (Practical Action 2010).

**Brick quality:** Hoffman kilns produce better colored bricks because of gas burning. Bricks from coal based HK have also good color and shape and duly get higher price in the market. VSBK cannot produce very good quality bricks as green bricks cannot be fired for long time inside the kiln. Vertical structure of this kiln may cause load variance resulting cracks in bricks if fired for a long time. So, strong bricks which are locally known as “pickets” and used instead of stone for concreting cannot be produced by VSBK. Bricks from Zigzag and FCK are of same average quality generally produced.

**Investment opportunity:** In terms of initial investment, FCK, Zigzag or VSBK require expenditure in the range of US$ 50,000 to 70,000 (Practical Action 2010). The conversion of
FCK to Zigzag requires only US$ 30,000 and thus not much burden and uncertainty to future business and return.

Hoffmann kiln is quite expensive requiring an initial investment of at least US$ 600,000. Coal based HK also requires an initial investment of about US$ 600,000 to 700,000 (Clean Energy Alternatives 2011). One major reason for the cost-variance between coal based HK and Hoffmann is, in coal based HK an additional drier is required to dry the green bricks by utilizing the waste heat of the flue gases. This modification also reduces pollution to some extent. Similar modification could be done for gas-fueled Hoffmann but due to its low pollution level, this modification can be considered superfluous unless otherwise justified by economic analysis. These kilns can operate round the year. Building Hoffmann kiln requires special expertise and thus demands high skill engineering consultants.

Working capital requirement for FCK and Zigzag kilns is approximately US$ 20,000 to 22,000 but for a Hoffmann it can go beyond US$ 100,000 because of higher inventory, maintenance and overhead costs (CDM 2007).

**Production rate:** Hoffmann kiln has a production capacity of 7.5 to 9 million bricks per season (CDM 2009). Coal based HK has a production capacity of around 15 million bricks as preheated and dehydrated green bricks require less time for burning (CDM 2007). FCK and Zigzag have approximately the same production capacity of around 2.5 million bricks per season as both the kilns are usually built in the low-lying land (CDM 2007). An ordinary VSBK has a production capacity of 2.7 million bricks and can operate all-round the year (Practical Action 2010). The production capacity of VSBK can be increased several times simply by increasing the number of kiln shaft.

To visualize the characteristics of the above comparative analysis easily, a number of mentioned factors are shown in Table 5.4 below.

**Emission:** One of the major reasons of pollution from brick kilns is inadequate supply of air during combustion. Blowers are added to Zigzag and coal based HK to ensure enough air supply to kilns. In VSBK, air flows upward through natural convection. In Zigzag kiln, as air flows through the zigzag path, the coarse particles are obstructed and settle before it is discharged into the atmosphere. The combustion process improves as artificial draft is created by the addition of blower. Also scrubbers are used to remove fly ash and SO\(_x\) in the Zigzag kiln. In a scrubber, flue
gas is drawn into an underground water reservoir to clear solid particles before being released into the atmosphere. Scrubbing water has to be changed regularly to ensure the system works properly. However, brickfield owners often do not care as it requires additional workforce, unless otherwise monitored regularly by the government agency.

Hoffmann kiln shows better performance than other coal burning technologies in terms of pollution control. For coal based Hoffmann, flue gases are passed through dryer to preheat the green bricks. Hard particles clear up largely from the flue gas since it is obstructed into the stacks of green bricks. VSBK requires less fuel per brick basis, so automatically emits less. Theoretically there should not be much black smoke from VSBK but sometime due to un-burnt combustion, black smoke emits. Carbon dioxide emission from all four types of brick kilns is estimated and shown in Table 5.5 for comparison. Detailed computation is shown in Appendix. From this table, it is clear that VSBK emits least CO₂ followed by coal based HK and Zigzag than FCK.

Table 2.1: Comparison of various key factors for different brick kilns

<table>
<thead>
<tr>
<th>Item</th>
<th>FCK</th>
<th>HK (coal)</th>
<th>Zigzag</th>
<th>VSBK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Requirement</td>
<td>16,000 m²</td>
<td>50,000 m²</td>
<td>16,000 m²</td>
<td>4,000 m²</td>
</tr>
<tr>
<td>Brick shape and color quality</td>
<td>Medium</td>
<td>Higher-medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Investment requirement (US$)</td>
<td>55,000</td>
<td>700,000</td>
<td>70,000</td>
<td>70,000</td>
</tr>
<tr>
<td>Working capital (US$)</td>
<td>22,000</td>
<td>100,000</td>
<td>22,000</td>
<td>22,000</td>
</tr>
<tr>
<td>Production rate/day</td>
<td>17,000</td>
<td>50,000</td>
<td>17,000</td>
<td>9,000</td>
</tr>
<tr>
<td>Production days/year</td>
<td>150</td>
<td>300</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>Coal required per 100,000 bricks</td>
<td>24 ton</td>
<td>14 ton</td>
<td>18 ton</td>
<td>10 ton</td>
</tr>
</tbody>
</table>

Table 2.2: CO₂ emission comparison from different brick kilns

<table>
<thead>
<tr>
<th>Item</th>
<th>FCK</th>
<th>HK (coal)</th>
<th>Zigzag</th>
<th>VSBK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific fuel consumption (TJ/brick)</td>
<td>4.02 ×10⁻⁶</td>
<td>2.35 ×10⁻⁶</td>
<td>3.02 ×10⁻⁶</td>
<td>1.68 ×10⁻⁶</td>
</tr>
<tr>
<td>CO₂ emission per 100,000 bricks (tCO₂e)</td>
<td>38.06</td>
<td>22.20</td>
<td>28.54</td>
<td>15.86</td>
</tr>
</tbody>
</table>

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2.4.7 Transition of Australian brick industry

In Australia, the early brick makers burnt their bricks in the open in a large heap which is popularly known as the Clamp kiln. This type of kiln was used for more than thousands of years throughout the world. Firewood or sometimes coal is used as fuel. This Clamp kiln was built of bricks that were to be fired. Temperature was difficult to control in these kilns. The quality of bricks produced from this kiln was unpredictable and generally poor. During the firing process one fifth of the bricks were destroyed or were insufficiently fired and had to be fired again.

As the industry expanded, permanent kilns were built. The earlier ones were of the intermittent type, which was, they had to be loaded, sealed, heated, cooled and unloaded for every firing. Actually the kiln was subjected to intermittent heating and cooling. Many were of up-draught design whether circular or square in size, with the furnace at the bottom and flue at the top. The version of the up-draught model was simply a square box which was open at the top with firing ports around the base. Up-draught kilns were wasteful of fuel, because a large portion of the energy produced was simply released into the atmosphere. As the down-draught kiln was more efficient it eventually replaced the up-draught kiln.

The kilns that eventually became quite popular in Australia were the down-draught type. The size of this kiln was often rectangular in plan with a fixed roof; however some circular kilns were also made. Furnaces at the sides sent the hot gases up the walls but then gases had to flow downward between the bricks to exit via flues in the kiln floor. Flue gases were led underground to a chimney stack nearby. This design was more efficient because the flame spent more time in contact with the bricks. The down-draught kilns were reliable and long lasting and produced attractive and well-fired bricks.

Coal or coke was adopted as the fuel in most large brick kilns. Wood also remained the preferred fuel in these kilns. The down-draught kilns had a fuel to load ratio of about 1:5; that is a ton of fuel was required for five tons of bricks (DENR 2008).

The mechanization of the brick work has been discussed in the 1860s and attempts were made to produce brick machines and refine kiln design but these initiatives seemed to be experimental that did not reach mass production or gain widespread practice. The Hoffman Company was the first brickworks to introduce mechanization on a large scale (DENR 2008).
With the introduction of continuous kilns, there had been a fundamental change in the technology of brick manufacturing. The Hoffman kiln having the continuous kiln design was widely used in Australia. The principle of the Hoffman kiln anticipated the twentieth century mass production. Though the original Hoffman kiln design had a circular plan, but they were more frequently built as a rectangular plan with straight parallel sides and semi-circular ends in Australia.

Hoffman’s first innovation was the introduction of mass production using steam-powered brick machines and continuous burning inside the kilns. There was no guarantee that the company could sell the output which was a new type and new size of brick. Also as the production method was new in Australia there was no guarantee that the technology would work in the long run.

However, as the Hoffman kilns reduced the cost of brick production, it introduced an economy of sale which brought a dramatic improvement in the efficiency of brick manufacturing. Hoffman dominated the brick making industry in Australia from the First World War to the 1970s. The production was up to 300,000 bricks in a single firing. These kilns were also efficient at that moment. Wastage of bricks in firing was negligible. Fuel-to-load ratio in a Hoffman kiln was about 1:20 (DENR 2008). All the major brick making companies had to keep up the brick supply to these kilns by installing wire-cutting or pressing machines. The capacity of the Hoffman kilns encouraged mechanization of the brick industry. The efficiency of the Hoffman kilns and the mechanization in the sector was the economic breakthrough that brought brick manufacturing into the mass housing market.

The interesting thing about the technologies of this sector in the late nineteenth century and the beginning of twentieth century was that it acted to de-skill the operation of the brickworks. At the workers level, jobs were specialized into task specific work. Work was paid according to production levels. Although significant elements of the brick production remained substantially same as in the 1890s, there was evidence of modifications to the production process to modernize it. In the 1940s many brick kilns converted from coal to oil firing, later when the oil prices increased in the early 1970s, the kilns were converted to natural gas firing. The processes here reflect the changing prices and availability of energy (Stuart 1989).
The first Hoffman was built around 1880s. The last Hoffman kilns went out of service in the 1980s in Australia, a century after the first one was built. Since the 1960s Hoffman kiln has been replaced by another continuous type of kiln called Tunnel kiln.

After replacement of Hoffman kilns by Tunnel kilns in Australia, the performance of these Tunnel kilns were improved over the years. Often the kilns were upgraded by introducing efficient burners, automation in gas control of the burners, better insulation, reduction of heat leakage, improving electrical demand control, adding doors to the end of the kiln, etc (Energy Efficiency Opportunities 2007). Inefficient Tunnel kilns were also replaced by modern efficient ones.

**Business strategies of Australian brick industry**

During the mid-nineteenth century, the brick industry was isolated on regional basis. Any excess amount needed was supported by mobile brick-makers. Some brick-makers worked part-time as brick manufacturing was not their main occupation. At the end of nineteenth century as railway networks began to provide a regional transportation network, allowed the reduction of transport costs to expand the market by providing incentive to mechanization. Many of the regional brick kilns closed and the more efficient mechanized brick kilns were adopted in others. However handmade brick kilns were not completely eliminated at that time. During the time of depression in late nineteenth century, construction works virtually stopped and vicious price war occurred (Stuart 1987). Large companies were forced to close down production and lay off workforce. Handmade brickworks suffered the most from this situation.

To revive from this situation, brick industry formed co-operative organizations to share work and regulate prices and quality. Formation of this co-operative organization caused high prices, poor quality bricks, refusal to supply, and various other monopolistic activities. Government sometimes tried to control the monopoly of the co-operative organizations by developing state-run brick kilns. Sometimes disgruntled builders set up their own brick kilns to keep pressure on the co-operative societies. Most of these incidents occurred during the first half of the twentieth century. During present time the brick industry has undergone some significant transformation. According to industry experts the sector has reached to its declining stage of life (Kelly 2012). The issue that is going to affect this sector most is the current introduction of carbon tax. Detailed impact of carbon tax to this industry is discussed in the following section.
Carbon price mechanism
The carbon price mechanism is going to be implemented in two stages. For the first three years, starting from 1 July 2012, the price of each ton of carbon pollution is fixed, like a carbon tax. Then, from 1 July 2015, the carbon pricing mechanism will move to an emissions trading scheme where the price will be set by the market (Australian Government 2011). According to the carbon price mechanism, the carbon price is now $23 for each ton of pollution beginning on 1 July 2012 (Frontier Economics 2011). The price will rise by 2.5 per cent a year during a three-year fixed price period until 1 July 2015. The carbon price mechanism will then transition to an emissions trading scheme where the price will be determined by the market. Around 500 businesses will be required to pay for their pollution under the carbon pricing mechanism.

According to the government, carbon price is the most cost-efficient way to cut carbon pollution as putting a price on pollution will encourage companies to innovate and invest in new technologies to use energy more efficiently.

Effect of carbon price in brick sector
Australian brick sector generates $1.1 billion revenue (in 2012), which is declining currently at a rate of 2% between 2008 and 2013 (Kelly 2012). Profit from brick sector is $187 million while a limited export earns $12.5 million only. Three companies share majority of the market of the brick sector in Australia. Brickworks Ltd has the major share of 27% whereas Boral Ltd has a share of 25% and CSR Limited has a share of 23%. A big portion of the brick industries are located in Victoria whereas 25% is located in NSW, 18.8% in Queensland, 18.6% in Western Australia, 6.3% in South Australia and 1% in Tasmania (Kelly 2012).

The principal output of this industry is clay bricks, which account for about 90% of industry revenue and 85% of the volume of production. Premium bricks are being the main bricks used for residential construction while the inferior quality bricks are satisfactory for use as non-facial bricks, underground or support walls. The wholesale price of premium brick ranges from about $475 to $600 per 1,000 and the bricks are delivered in strapped packs of 264 to 300 (Kelly 2011).

Collectively the brick industry employs 30,000 people, produces approximately 1.6 billion bricks annually and contributes $2.6 billion to the Australian economy. The brick industry is also a
significant provider of apprenticeships and training with investment of over $3.5 million annually (Kelly 2012).

The industry is currently considered to be moving into the declining stage of its life cycle, with demand heavily dependent on cyclical fluctuations in residential construction investment. On the top of it the industry is increasingly impacted due to the lower demand of bricks in the housing construction. Brick market in Australia is facing difficult condition due to product substitution by non-ceramic building materials, such as - timber, stone, concrete and steel (Kelly 2011).

As the brick industry operates within the building product market that includes a large number of substitutes, it is hard for the brick industry to pass the carbon tax to the consumers as some of the substitutes have significantly less emission compared to brick kilns. However, these substitutes within the building product market vary greatly in their ability to provide energy efficient housing or reduce the long-term emissions associated with maintenance and replacement. Lightweight building products may have lower production emissions but require more maintenance, need to replace more frequently and creates less thermally efficient buildings. Whereas, bricks have higher production emissions but require almost no maintenance or replacement and provide a more thermally efficient building. Hence it becomes a matter of debate whether people should continue to use more bricks than other substitutes. Comparison of CO₂ generated per kg of clay bricks and some of the substitute products found from life cycle assessment is presented in Table 2.3. This comparison clearly shows that clay bricks are emitting less greenhouse gases compared to some of the substitute products.

Table 2.3: Bricks and some other substitutes’ emission comparison (Hammond 2008)

<table>
<thead>
<tr>
<th>Materials</th>
<th>kgCO₂ released per kg of production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay bricks</td>
<td>0.22-0.46</td>
</tr>
<tr>
<td>Concrete (AAC’s)</td>
<td>0.28-0.376</td>
</tr>
<tr>
<td>Timber</td>
<td>0.46-0.86</td>
</tr>
<tr>
<td>Stone</td>
<td>0.056-0.187</td>
</tr>
<tr>
<td>Steel</td>
<td>0.42-2.75</td>
</tr>
</tbody>
</table>

The capital costs in the brick industry are relatively high and no technology currently exists to significantly reduce the emission intensity of the industry. Furthermore existing technologies, which currently have life spans of 30-50 years, have no alternative usage to convert into low
carbon emission technology. The emission levels fluctuate with the building cycles between 1200 and 1500 tons of CO₂-e per million dollars of revenue. (Think Brick Australia 2008).

The domestic market for clay bricks is also shrinking due to the trend toward smaller and higher density dwellings. The impact of carbon price will be distributed differently across the building product market and the brick sector will be affected significantly. Cheaper manufacturing cost of bricks in Asia and other parts of the world will increasingly encourage import of bricks to substitute local manufacturing. In Malaysia and other parts of Southeast Asia, the industry has excess capacity to produce cheaper bricks. And the cheap transport cost means that the brick can enter Australia and compete with local bricks. The brick industry in Australia estimates that bricks used for internal walls can be imported from Malaysia at the price which is equal to current price in Australian industry (Think Brick Australia 2008). So, increase in brick price due to carbon tax will compel import from overseas. Thus there will be decrease in the size and future investment in the Australian brick industry.

Ultimately the biggest problem that is going to be faced by the brick industry is by product substitution. Though majority of the brick industry is controlled by three brick companies, a significant fraction of the brick sector still includes many local manufacturers who service regional Australia through investment and employment. These regional manufacturers will be more impacted because of their inability to absorb costs. Passing of this cost to the buyers will further increase product substitution.

2.5 Modelling Using Computational Fluid Dynamics (CFD)

2.5.1 Modelling

Computational Fluid Dynamics (CFD) is a computer-based tool for simulating the behavior of systems involving fluid flow, heat transfer, and other related physical processes (Andersson 2012). It works by solving the equations of fluid flow (in a special form) over a region of interest, with specified (known) conditions on the boundary of that region.

The set of equations that describe the processes of momentum, heat and mass transfer are known as the Navier-Stokes equations. These partial differential equations have no known general analytical solution but can be discretized and solved numerically. Equations describing other
processes, such as combustion, can also be solved in conjunction with the Navier-Stokes equations (ANSYS 2009).

There are three major numerical methods that are used in CFD solutions – Finite Difference (FD), Finite Volume (FV) and Finite Element (FE) methods. In FD, each nodal point of the grid is used to describe the fluid flow domain. Taylor series expansions are used to generate FD approximations to the partial derivatives of the governing equations (Tu et al. 2013). In FE the governing equations are first approximated by multiplication with the shape functions before they are integrated over the entire computational domain (Tu et al. 2013). The most common and the one on which CFX is based, is known as the Finite Volume technique. In this technique, the region of interest is divided into small sub-regions, called control volumes. The equations are discretized and solved iteratively for each control volume. As a result, an approximation of the value of each variable at specific points throughout the domain can be obtained. In this way, the behavior of the flow can be identified.

2.5.2 Simulation steps using CFD

There are many commercial general-purpose CFD programs available, e.g. Fluent, CFX, OpenFOAM, Flow 3D are few to cite. In all CFD programs the following steps in general are followed to solve a particular problem. In this research to simulate Tunnel kiln performances ANSYS CFX has been used. Figure 2.14 is showing the CFD simulation steps using available any general-purpose CFD program including ANSYS CFX.

ANSYS CFX is the CFD software from ANSYS Inc. Solving any CFD problem using ANSYS software package has to include ANSYS Workbench, ANSYS Design Modeller, ANSYS Mesh, ANSYS CFX-Pre and ANSYS CFX-Post. Here, ANSYS Workbench is the platform where all the components of the software can be linked up to solve a particular problem. The purposes of other software components are mentioned later.

Geometry modelling

A simulation problem using CFD starts with a two-dimensional (2D) or three-dimensional (3D) drawing of the geometry of the system. A Computer Aided Design (CAD) program is included in all commercial CFD programs, however the geometry of the system can also be drawn separately in any standalone CAD program and imported into the CFD grid-generation program. CAD
programs not designed for CFD often contains details that cannot be included in CFD simulation drawing. The drawing must be cleaned before they can be included in the meshing program. For this research, kiln geometry needs to be drawn in ANSYS Design Modeller.

![Flowchart: Simulation Steps Using CFD Program](image)

**Modelling of Geometry**
- Defining geometry and boundary

**Generating Mesh**
- Divide the geometry into small computational cells called mesh

**Defining models**
- Define models for turbulence, chemical reactions, radiation, COx, NOx emissions etc

**Set properties**
- Heat transfer coefficient, temperature, velocity etc

**Set boundary and inlet conditions**
- Setting up initial conditions, inlet and outlet conditions and wall conditions

**Solve**
- Chose iteration methods, transient or steady state, convergence value to obtain results

**Post-processing**
- Analyze the result

*Figure 2.14: Flowchart to show the simulation steps using CFD program*

**Grid generation (meshing)**
The equations for momentum transport are nonlinear which means that the computational volume must be discretized properly to obtain an accurate numerical solution of the equations. Accurate meshing of the computational domain is as important as defining the physical domain as stated above. An ill conditioned mesh can give rise to very inaccurate results, so the quality of
the mesh, e.g. the aspect ratio and skewness must be evaluated prior to the simulation (Andersson et al. 2012). This research on brick kiln has a complex geometry to draw at the beginning and then requires consistent meshing. So several types of meshing needs to be generated to find out whether the geometry is mesh independent. Meshing for this particular problem is drawn in ANSYS Mesh.

**Define models**

For single-phase laminar flow the Navier-Stokes equations can be solved directly but for turbulent and multiphase flows the user must select the most appropriate models. There are few generally accepted models for turbulence and multiphase flows, but there are hundreds of models to choose from (Andersson et al. 2012). For each model there are also several parameters that must be set for proper simulation. Usually the default values are the best choice but in some cases the user can find more suitable parameters to be chosen according to the problem in consideration. In most commercial CFD programs it is also possible to write users own model as a user defined subroutine/function (UDS/UDF). This research involves single phase turbulent flow as gas and air react in combustion to generate heat and emissions all in gaseous phase. In this regard appropriate models have to be selected for simulation. In ANSYS CFX these models has to be chosen from options of CFX Pre. For turbulence modelling, k-epsilon model is chosen, for radiation modelling P1 model is chosen, and methane-air reaction is chosen from ANSYS library. Detailed descriptions of these models are given in Chapter 3.

**Set properties of different parameters**

All physical properties like viscosity and density of the fluids must be defined according to their temperature and pressure distribution. Some are inbuilt into the CFD software or available in their databases. It is also possible to write a UDS/UDF and added to the CFD program for calculating the properties. However for this particular research, properties were selected from options available in ANSYS CFX Pre. The chosen properties of different parameters are described in Chapter 4.

**Boundary and initial conditions**

Boundary conditions must be defined including walls and other boundaries such as air inlet and outlet temperatures, velocity, pressure, etc. Geometrical symmetries must also be defined. Defining symmetry ensures less computation and hence quick result. Initial conditions for
transient simulations or an initial guess to start the iterations for steady-state must also be provided. In this study, boundary conditions for kiln air inlet and outlet, gas inlet and outlet, symmetry of the geometry have to be provided for computation. Also brick wall temperatures have to be provided as an initial guess for proper estimation during subsequent iterations. These values are given using ANSYS CFX Pre.

**Solve**

In CFD, the quality of an acceptable solution in terms of convergence criteria must also be defined. Whether the fluid flows is steady or unsteady that also has to be mentioned for computation. This particular problem involves combustion. Firing of Tunnel kiln burner once started continues for months until operator shuts it for maintenance or emergency. Though initially fluid temperature is unsteady, becomes steady quickly due to stability in gaseous flow distribution. So it is considered that the simulation should be performed under steady-state condition. For high accuracy convergence value is given as $1 \times 10^{-4}$. In CFD the equations for continuity, momentum, energy, radiation and combustion are solved simultaneously. After solution, results at different format can be viewed in CFX Post.

**Post-processing analysis**

The first objective in the post-processing is to analyze the quality of the solution. It has to be found out whether the solution is independent of the grid size or the convergence criterion. It has to be checked whether proper turbulence model and boundary conditions were chosen. Analysis of the final simulation results can give local information about resulting fluid flows, temperature distribution, emission generated, etc. In this study, it has been checked whether the simulation is independent of generated mesh or grid size. In ANSYS, post processing analysis can be performed using CFX Post.

**2.6 Importance of Using CFD Analysis in Brick Kilns**

**Previous researches in this field**

An in-depth review of the available literature reveals that not many researches applied Computational Fluid Dynamics (CFD) to evaluate the performance of fuel combustion inside a brick kiln. Most of the research found on the application of CFD in Tunnel kiln is related to realize the combustion situation and how to improve the burner efficiency (Sheng et al. 2004;
Majority of these simulations are modelled in two dimensions; three-dimensional modelling was largely overlooked due to complexity. Research is also conducted to find out the optimum placement of the burner (Hauck 2005). There are quite a few researches where mathematical models of the cooling, preheating and firing zones of a Tunnel kiln were developed to increase its efficiency (Mancuhan 2009; Kaya et al. 2007, 2008, 2009). There are researches that considered the emission performances of kilns/burners used for other sectors. CFD application in similar other sectors include optimizing the design of different types of burners and emission performances (Chacon et al. 2007), drying and thermodynamic processes (Jamaledidine et al. 2010; Rasul et al. 2007), gas flow mixing, secondary airflow analysis (Yang et al. 1999; Purimetla et al. 2009), etc. CFD is also used in combustion related problems including prediction of field of combustion for coal burner in rotary kiln (Ai-chun et al. 2006), and coal-air balancing in power plant (Vijapurapu et al. 2006). Heat transfer efficiency of counter travelling Tunnel kiln was analyzed where the brick stacks move in opposite directions in two side by side tunnels (Meng 2011). This method of heat transfer in counter travelling Tunnel kiln is popularly known as solid-solid recuperation. In this method, heat is extracted from brick body by air and is released to the other counter travelling Tunnel kiln. Simulation is also conducted for analyzing the flow in Hoffman kiln (Garcia et al. 2006). Though there are few researches that evaluated the performance of a Tunnel kiln using CFD analysis (Meng 2011; Sheng et al. 2004; Hauck 2005), but none of them considered emission performances of those kilns. However, researches that considered emission performances of those kilns didn’t include CFD simulation (Co et al. 2009; Maithel et al. n.d.; Greentech knowledge solutions 2012). Few researches also tried to identify the optimum Tunnel kiln curve for various ceramic products (Durakovic et al. 2006; Oba et al. 2011; Atanasov et al. 2007). Industries emphasize on optimum Tunnel kiln curve for obtaining various quality bricks and ceramics. So, from the generated Tunnel kiln curve point of view, brick kiln design need to be optimized.

Research Gap
From the literature review, it has been identified that there is no such research that focused on optimizing the Tunnel kiln design for typical clay bricks using CFD simulation. So the research question is - what is the optimum temperature distribution curve for the Tunnel kiln to ensure efficient fuel usage and thus can reduce emission?
Significance of this research

The purpose of this research is to use this popular tool to evaluate the performances of the brick kiln in three dimensions and identify ways to improve its emission performance. Incomplete combustion and emission are related to improper kiln/burner design. Emissions to air from natural gas fired kilns usually consist of carbon-dioxide, carbon monoxide (CO_x), sulphur dioxide (SO_2), sulphur trioxide (SO_3), oxides of nitrogen (NO_x), gaseous fluoride/chloride compounds, particulate matters, etc. ANSYS CFX has its own library for few common reactions. Reaction between methane and air can be found from that library. That equation does not consider SO_x or chloride, fluoride emissions. Also the composition of gas used by various competitors in the industry may vary according to the location of the factory and available gas source nearby. So for problem simplification, only NO_x and CO_x emissions from the brick kilns are investigated using available reaction equation from ANSYS library.

Brick kiln environment is drawn in 3D using CFX Design Modeller. Appropriate turbulence, emission, radiation, and combustion models are identified from previous researches (Jamaleddine et al. 2010; Chacon et al. 2007). Inlet and outlet cross-sectional areas, velocities, air temperatures, stack bricks heat transfer coefficient and its initial guess of temperature and other properties along with fuel composition are provided as input.

As Computational Fluid Dynamics simulation is an integral part of this research, in the following chapter, detailed Computational Fluid Dynamics theories and the relation of these theories for this problem is explained. Also, how these theories can be implemented in this case using ANSYS CFX is described.

2.7 Summary

Brick is the chief construction material worldwide and is considered as a weight bearing or partitioning building unit. The processes of manufacturing brick include extraction of clay, moulding and shaping, drying and firing and cooling to finished product. Firing is a key process in the production of bricks, as it controls the vitrification process and is usually completed by 1050°C for ordinary building bricks.

There are different types of kilns for brick production from ancient times. Tunnel kiln is operated in developed countries whereas Fixed Chimney, Zigzag, Hoffman, Vertical Shaft Brick Kiln
VSBK) operate in developing countries. Tunnel kiln is evaluated in this research to improve its performance.

Computational Fluid Dynamics (CFD) is a computer-based tool for simulating the behavior of systems involving fluid flow, heat transfer, combustion, and many other processes. CFD simulation involves modeling geometry, generating mesh, defining models, setting parameter properties, and boundary and initial conditions, solving and post-processing. The purpose of this research is to use this popular tool to evaluate the performance of the Tunnel kiln in three dimensions and identify ways to improve its performances.
Chapter 3
Computational Fluid Dynamics Modelling using ANSYS CFX

3.1 Introduction

Computational fluid dynamics (CFD) is used to simulate fluid flow characteristics. CFD simulation without proper knowledge can be a very uncertain tool. The commercial CFD programs have many default settings and can almost always give results from the simulations, but to obtain reliable results the model must be chosen with a logical methodology. A converged solution displays the results of the specifically chosen models with the given mesh. However it may not reveal the truth. Without proper understanding of the CFD program and the modelling theories behind it, CFD can be limited to colorful fluid display. To understand CFD simulation properly, fluid flow characteristics needs to be understood along with the provided options of the CFD software.

3.2 Fluid Flow Characteristics

From the CFD modelling point of view it is useful to separate possible flows into the following categories: laminar-turbulent, steady-unsteady-transient and single phase-multiphase.

The highly ordered fluid motion characterized by smooth layer of fluid is called laminar. In laminar flow the Navier-Stokes equations that describe the momentum transport of flow, is dominated by viscous force. It is possible with CFD to obtain very accurate flow simulations for single-phase laminar flow. On the other hand the highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations is called turbulent. The Navier-Stokes equations describe turbulent flows, but, due to the properties of the flow, it is seldom possible to solve the equations analytically for real engineering applications. From CFD simulation it is possible to closely predict the characteristics of a turbulent flow. Air and gas flows inside the brick kiln are turbulent in nature; hence the characteristics of turbulence are used to analyze the flow inside the kiln. However flows from turbulent to laminar and from laminar to turbulent (i.e. transitional flow) are difficult to simulate accurately (Andersson et al. 2012).
Steady flow is a flow that has no change at a point with time. A flow that is not steady is known as unsteady flow whereas, developing flows are considered as transient flow (Cengel et al. 2010). Brick kiln fluid flows however are not steady at the initial stage of firing when flows are yet to become stable. In course of time, temperature distribution inside the kiln becomes steady quickly due to stability in fluid flow.

Single phase flow consists of gas-gas or liquid-liquid systems. Very accurate solutions are obtained if single-phase laminar flow is simulated using CFD. If the flow is turbulent, in most cases satisfactory flow simulations can be obtained. The main problem is usually related to simulation of the mixing of reactants for fast reactions in laminar or turbulent flow (Andersson et al. 2012). When the reaction rate is fast compared to the mixing, a model for mixing along with a chemical reaction must be introduced. Combustion in the gas phase belongs to this category. In this study, the flow of air reacting with gas forms a single gaseous phase, which eventually releases heat to the object under consideration. In the process separate reaction equation was included which was solved simultaneously with the problem of gas and air mixing.

Multiphase flow may consist of gas-liquid, gas-solid, liquid-liquid, liquid-solid or gas-liquid-solid systems. For multiphase system containing very small particles that follow the continuous phase closely, reasonable simulation results can be obtained by CFD (ANSYS 2009). Systems in which the dispersed phase has a large effect on the continuous phase are more difficult to simulate accurately. Such as coal particles sprayed in gaseous mixture. Lack of good multiphase model deteriorates the quality of simulation. For gaseous combustion, multiphase flow is not necessary, however if coal based combustion is simulated then multiphase model is essential. In this particular research, only gas fueled kiln is considered. So, single phase flow is adequate for the simulation. However, if the coal fired kilns are considered then the characteristics of multiphase flow also needs to be considered.

3.3 ANSYS CFX

ANSYS CFX, a Computational Fluid Dynamics (CFD) software, combines advanced solver with powerful pre- and post-processing capabilities. It includes: a solver that is both reliable and robust; full integration of problem definition, analysis, and result presentation. It also has an intuitive and interactive setup process and uses menus and advanced graphics (ANSYS 2009). ANSYS CFX is capable of modelling: steady-state and transient flows, laminar and turbulent
flows, heat transfer and thermal radiation, transport of non-reacting components, combustion, particle tracking, etc.

### 3.3.1 Geometry modelling

The geometry of the fluid domain where the analysis can be performed is drawn using ANSYS Design Modeller. Often geometries can be drawn in other CAD software and then can be imported in ANSYS. However, geometries drawn in other CAD software may contain details that cannot be included in CFD simulation drawing and may require correction. So, it is better to use built-in drawing software ‘Design Modeller’ of ANSYS for modelling the geometry.

### 3.3.2 Meshing process

After drawing the geometry, it is discretized into small cells using ANSYS Mesh. Meshing can be accomplished in any geometry by the following steps. Figure 3.1 is showing how meshing is accomplished using ANSYS Mesh.

![Meshing process diagram](image)

Figure 3.1: Meshing process

A proper meshing method needs to be chosen at the beginning. Global mesh settings have to be specified which means what type of mesh is going to be generated to the overall geometry. Then local mesh settings are inserted if required. The part of the geometry with more importance may get higher spatial resolution by local mesh setting. Higher resolution means the number of local elements in that particular part can be increased by sub-dividing the larger elements.
Consequently, after generating the mesh, mesh quality needs to be checked. Mesh quality is extremely important for proper simulation. Better quality mesh ensures accurate result of the simulation.

Different 2D and 3D shapes formed by ANSYS Mesh are shown in Figures 3.2 and 3.3. There are five meshing methods available in ANSYS Mesh for 3D geometries. Tetrahedral method can be used to generate tetrahedral elements. Sweep method can be used to generate prism or hexahedral mesh for sweepable bodies. Hex dominant method is recommended for bodies that cannot be swept. A quad dominant surface mesh (as shown in Figure 3.3) is created first and then Hex mesh is used to fill most of the domain, and pyramid and tetrahedral meshes for rest of the domain. Multizone method mainly contains hexahedral elements in different defined zones. Automatic method combines multiple methods based on complexity of geometry. It is a combination of tetrahedrons (patch conforming) and sweep methods. This method automatically detects volumes that can be meshed with sweep method. Volumes that cannot be meshed using sweep method are meshed using tetrahedron method with patch conforming algorithm.

There are four meshing methods for 2D geometries available in the ANSYS Mesh as shown in Figure 3.3: Automatic method (Quad dominant), Triangles, Uniform Quad/Tri and Uniform...
Quad. The shapes as shown are self-evident to explain their advantages and disadvantages for use in the geometries.

![Triangle (Tri) and Quadrilateral (Quad)](image)

Figure 3.3: 2D shapes formed by meshing methods

After the generation of the mesh, mesh quality has to be checked. If the mesh quality is not of desired level for a particular method then other methods can be selected judiciously. Sometimes complicated geometry cannot be meshed using a particular mesh method. In that case, a different mesh method has to be chosen to generate mesh for that geometry. This geometry on Tunnel kiln is a three-dimensional body. Different 3D meshing options has been considered. Due to the complexity of the geometry, not all methods could generate mesh in this geometry. Hex dominant and Automatic methods are used to generate mesh in this geometry. After the generation of mesh, mesh quality was checked and mesh independency was analysed as explained later.

**Mesh controls**

Sometimes automatically generated mesh does not have adequate number of nodes or elements. In that case the number of nodes and elements can be increased by local and global mesh controls. Global mesh settings can be controlled using the following options: sizing, defeaturing, statistics, advanced options etc.

**Advanced sizing functions**

Advanced sizing function is used to control the size of mesh. This is an important tool to generate appropriate sized mesh required for faultless and effective simulation. Advanced sizing function controls the growth and distribution of mesh in important regions of high curvature or close proximity of surfaces. Five options of advanced sizing functions are as follows: Off – the edges are meshed with global element size computed by the Mesher. The edges are refined for
Curvature and 2D proximity. At the end, corresponding face end volume mesh is generated. Curvature – determines the edge and face sizes based on ‘curvature normal angle’ which is the maximum angle between adjacent face normals. Finer curvature normal angle creates finer surface meshes. Proximity – controls the mesh resolution on proximity regions in the model. It fits in specified number of elements in the narrow gaps. Higher number of cells across gap creates more refined surface meshes. Proximity and curvature – combines the effect of proximity and curvature size function. Fixed – constant mesh size throughout, no refinement due to curvature or proximity in the model. Surface mesh is generated with maximum face size. Volume mesh is generated with specified maximum size.

As proximity and curvature gives better meshing by controlling of the sizes, this option was chosen for this geometry. Due to the complexity of the geometry, ‘Fine’ mesh option under proximity and curvature could not be chosen for this geometry because the program ran out of memory. Instead ‘Coarse’ mesh option was chosen.

Element size
Defining element size is important to increase the number of elements and nodes. Element size can be defined for the entire model. This size is defined for meshing all edges, faces and bodies. A particular size for elements can be mentioned as per geometry dimensions. During meshing for this geometry, for global mesh controls, element size was chosen as 100 mm after several trial and error runs of the model. The local meshing can be controlled locally by scoping a combination of the following options to the geometry: sizing, refinement, face-meshing, inflation, etc. For local mesh control, a sizing of 65-80 mm was chosen for selected faces of this geometry.

3.3.3 Checking mesh quality
A good quality mesh is very important in order to minimize the errors in the solvers leading to numerical diffusion and incorrect results. A good mesh has 3 components: good resolution, appropriate mesh distribution and good mesh quality. The first two components depend on the overall meshing process and the user’s meshing strategies to conduct a specific type of analysis. ANSYS Mesh can quantify the mesh quality using several quality criteria and tools. It is very important to generate a mesh displaying good quality matrices as a necessary condition.
Orthogonal quality (OQ)

Orthogonal quality is a special quality of generated mesh which is defined by the following two equations:

For a cell it is: \( \frac{A_i \cdot f_i}{|A_i|} \times \frac{A_i \cdot c_i}{|A_i|} \) computed for each face \( i \)

For the face it is: \( \frac{A_i \cdot e_i}{|A_i|} \) computed for each edge \( i \).

where \( A_i \) is the face normal vector and \( f_i \) is a vector from the centroid of the cell to the centroid of that face, and \( c_i \) is a vector, \( e_i \) is the vector from the centroid of the face to the centroid of the edge as shown in Figure 3.4 (Leap Australia 2010). Perfect orthogonal quality is 1 whereas the worst orthogonal quality is 0. During solving this problem, from various mesh generation it was found that orthogonal quality was close to 0.8.

Skewness

Skewness is another characteristic to determine the quality of meshing. Perfect skewness value is 0, whereas worst skewness value is 1. In this modelling, it was found after mesh generation that skewness was very close to 0. There are two methods of determining skewness (Leap Australia 2010): i) Equilateral volume deviation, where skewness is defined as
Skewness = \frac{\text{optimal cell size} - \text{cell size}}{\text{optimal cell size}} \tag{3.1}

This equation applies only for triangles and tetrahedrons. Figure 3.5 shows how skewness is measured. ii) Normalized angle deviation, where skewness is defined as

\text{Skewness} = \max \left[ \frac{\theta_{\text{max}} - \theta_e}{\theta_e}, \frac{\theta_e - \theta_{\text{min}}}{\theta_e} \right] \tag{3.2}

where $\theta_e$ is the equiangular face/cell (60 for tets and tris, and 90 for quads and hexas). $\Theta_{\text{max}}$ and $\theta_{\text{min}}$ can be found from the Figure 3.6. $\Theta_{\text{max}}$ and $\theta_{\text{min}}$ are the maximum and minimum angles between any two edges of the cell, and $\Theta_e$ is the angle between any two edges of an ideal equilateral cell with the same number of edges (Cengel et al. 2010). In CFX, the vertex of the mesh-element is the centre of the solver-element as shown in Figure 3.7.

Figure 3.5: Measuring skewness

Figure 3.6: Measuring $\Theta_{\text{max}}$ and $\theta_{\text{min}}$
Orthogonality, Aspect Ratio and Expansion Factor

CFX solver calculates these three important measures of mesh quality at the start of a run and updates them each time the mesh is deformed.

Orthogonality measures alignment of: \( \text{ip-face normal vector} = n \), \( \text{node to node vector} = s \) as shown in Figure 3.8. Orthogonality factor > 1/3 is desirable and orthogonality angle > 20° is desirable. Aspect ratio measures how stretched a control volume is as shown in Figure 3.9. Aspect ratio = maximum of the ratio of largest to smallest ip-areas for each element surrounding a node, where < 100 is desirable (Leap Australia 2010).
Expansion factor measures how poorly are the nodal position corresponds to the control volume centroid as shown in Figure 3.10. Mesh expansion factor = ratio of largest to smallest element volumes surrounding a node, where < 20 is desirable (Leap Australia 2010).

![Figure 3.10: Defining expansion factor](image)

After generating mesh of the Tunnel kiln geometry, it was found that orthogonality, aspect ratio and expansion factor had desired values.

### 3.4 Equations in ANSYS CFX

#### 3.4.1 Continuity, momentum and energy equations

The momentum and continuity equations need to be solved for CFD simulation. The equation of the conservation of mass or continuity can be written as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \left( \rho \vec{v} \right) = S_m
\]  

(3.3)

Conservation of momentum in an inertial reference frame is given by:

\[
\frac{\partial}{\partial t} \left( \rho \vec{v} \right) + \nabla \left( \rho \vec{v} \vec{v} \right) = -\nabla p + \nabla (\tau) + \rho \vec{g} + \vec{F}
\]

(3.4)

where \( \rho \) is the density, \( \vec{v} \) is the velocity, \( S_m \) is the source term, \( p \) is the static pressure (Pa), \( \tau \) is the stress tensor, \( \vec{F} \) is the external body forces, \( \vec{g} \) is the gravity, \( t \) is the time (Chacon et al. 2007).

Energy equation needs to be solved if heat transfer is included in the problem. As this research contains combustion and heat transfer related issues so energy equation needs to be incorporated. Heat transfer in a fluid domain is governed by the energy equation given below:
\[
\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}(\rho E + \rho)) = \nabla \left( k_{\text{eff}} \nabla T - \Sigma \vec{J} + (\tau_{\text{eff}} \vec{v}) \right) + S_h
\] 

(3.5)

where \( E \) is the energy term, \( \vec{v} \) is the velocity, \( \rho \) is the density, \( k_{\text{eff}} \) is the effective turbulent kinetic energy, \( T \) is the local temperature in Kelvin, \( h \) is the enthalpy for ideal gas, \( \vec{J} \) is the diffusion flux, \( \tau_{\text{eff}} \) is the effective stress tensor, \( S_h \) is the volumetric heat source term, \( t \) is the time (Chacon et al. 2007).

Different options selected in ANSYS CFX solve the above equation in different ways. If ‘None’ is selected in the CFX Pre then energy transfer equation is not solved. While ‘Isothermal properties’ are selected, the energy transport equation is not solved. However, a temperature is required to evaluate consequent fluid properties. ‘Total energy’ option models the transport of enthalpy and includes kinetic energy effects. It should be used for gas flows and high speed liquid flows where kinetic energy effects become significant. For multi-component flows, reacting flows and radiation modelling, additional terms need to be included in the energy equation. If ‘Thermal energy’ is selected, an energy transport equation is solved which neglects variable density effects. In this modelling objective, thermal energy is the most suitable option to solve the problem.

### 3.4.2 Radiation model

Radiation effects should be considered when \( Q_{\text{rad}} = (T_{\text{max}}^4 - T_{\text{min}}^4) \) is significant compared to convective and conductive heat transfer rates. In this particular research convective heat transfer is significant compared to conductive and radiative heat transfer.

To find out the effect of radiation, Radiative Intensity Transport Equations (RITEs) are solved. Several radiation models are available in ANSYS CFX which provides approximate solution to the RITEs. Each radiation model has its own assumptions, limitations and benefits. In ANSYS CFX there are four models available – i) Rosseland model, ii) P1 model, iii) Discrete transfer model, and iv) Monte Carlo model.

Before choosing a radiation model, it needs to be found out whether the fluid is transparent to radiation at wavelengths where the heat transfer occurs or whether that fluid absorbs and re-emits the radiation. If the fluid absorbs and re-emits radiation then P1 model is a good choice. Many combustion simulations fall into this category since combustion gases tends to absorb radiation. P1 model gives reasonable accuracy without too much computational effort. This model has
proved adequate for the study of fuel flames, in regions away from the immediate vicinity of the flame. However, it has been used for lower temperature values with varying success. The radiative transfer equation adopted for an absorbing, emitting and scattering medium at position \( \mathbf{r} \) in the direction \( \mathbf{s} \) is:

\[
\frac{dl(\mathbf{r}, \mathbf{s})}{ds} + (\alpha + \sigma_S) I(\mathbf{r}, \mathbf{s}) = a n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_S}{4\pi} \int_0^4 \! I(\mathbf{r}, \mathbf{s}) \phi(\hat{s}, \mathbf{s}) d\Omega.
\]

(3.6)

where \( I \) is the radiation intensity, \( \mathbf{r} \) is the position vector, \( \mathbf{s} \) is the direction vector, \( \hat{s} \) is the scattering direction vector, \( \alpha \) is the absorption coefficient, \( \sigma \) is the Stefan-Boltzmann constant, \( n \) is the coefficient of excess of air, \( T \) is the local temperature in Kelvin, \( \sigma_S \) is the scattering coefficient, \( \phi \) is the phase function, \( \Omega \) is the solid angle, \( G \) is the incident radiation, \( C \) is the linear anisotropic phase function coefficient, \( t \) is the time. (Chacon 2007).

The following equation is obtained for the radiation flux:

\[
q_r = \frac{1}{3(a + \sigma_S) - C\sigma_S} \nabla G
\]

(3.7)

If the fluid is transparent to radiation at wavelength where the heat transfer occurs then Monte Carlo or Discrete transfer models (DTM) may also be used. DTM can be less accurate in models with long/thin geometries. Monte Carlo uses the most computational resources, followed by DTM. As this particular research involves simulation of combustion so P1 model is selected.

For effective heat transfer, proper defining of boundary conditions are essential. For inlet, static temperature or total temperature has to be given. For opening, opening temperature or opening static pressure has to be provided. Wall can be selected as fixed temperature, adiabatic, heat flux or heat transfer co-efficient. Sometimes, if outlet is assigned in ANSYS CFX, it causes error in computation. In such cases “Opening” is selected which allows fluid either enter or exit the domain as per the prevailing condition.

Natural convection occurs when temperature differences in the fluid result in density variations. For heat transfer problems, sufficient iterative computation time has to be allowed for heat balance simulation. Wall heat transfer coefficient \( h_c \) usually depends on the wall adjacent temperature. Wall heat flux \( q_w \) is the total heat flux into the domain by convective and radiative processes.
3.4.3 Turbulence

Turbulence is unsteady, irregular motion in which transported quantities (mass, momentum, scalar species) fluctuate in time and space. Fluid properties and velocity exhibit random variations. Theoretically all turbulent and laminar/transition flows can be simulated by numerical solution of the full Navier-Stokes equations. A large number of turbulence models are available in CFX, some have very specific applications while others can be applied to a wider category of flows. The velocity near the wall is important. Turbulence models are generally suited to model the flow outside the boundary layer.

Turbulence models are used to predict the effects of turbulence in fluid flow. There is no turbulence model that has universal acceptability of dealing with all problem areas. The choice of turbulence model depends upon various considerations such as flow characteristics, level of accuracy, available computational resources, and time availability for simulation. To make the most appropriate choice of a model for the brick kiln, it was necessary to understand the capabilities and limitations of those various models discussed below.

A number of models have been developed that can be used to approximate turbulence. Some of these have very specific applications, while others can be applied to a wider class of flows. The turbulence models available in CFX are: k-ω model, Standard k-ε model and Shear Stress Transport (SST) model, etc.

Standard k-ε model

Standard k-ε model offers a good compromise between numerical effort and computational accuracy. Limitations of this model are due to inaccuracies with swirl flows and flows with strong streamline curvature ANSYS (2009).

For this particular study, k-ε model has been selected. The k-ε model equations can be expressed as follows:

\[
\frac{\partial}{\partial t} (\rho_m k) + \nabla (\rho_m \bar{v}_m k) = \nabla \left( \frac{\mu_t}{\sigma_k} \nabla k \right) + G_{k,m} + G_b - \rho_m \varepsilon \tag{3.8}
\]

\[
\frac{\partial}{\partial t} (\rho_m \varepsilon) + \nabla (\rho_m \bar{v}_m \varepsilon) = \nabla \left( \frac{\mu_t \mu_m}{\sigma_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k} (C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon) \tag{3.9}
\]
where, $\rho_m$ is the mixture density, $\vec{v}_m$ is the velocity, $\mu_t$ is the turbulent viscosity, $G_{k,m}$ is the production of turbulence kinetic energy, $G_b$ is the production of turbulence kinetic energy because of buoyancy, $k$ is the turbulent kinetic energy, $\epsilon$ is the turbulent dissipation rate, $C$ is the linear anisotropic phase function co-efficient, $\sigma_k$ and $\sigma_\epsilon$ is the scattering coefficient for $k$ and $\epsilon$, $t$ is the time (Chacon et al. 2007).

**k-\omega model**

This model has few advantages among which are the near wall treatments for low-Reynolds number computations. Low Reynolds number computation means the near wall mesh is fine enough to resolve the laminar part of the boundary layer which is very close to the wall.

**Shear Stress Transport (SST) model**

The SST model is based on the k-\omega model and has the same automatic wall treatment like k-\omega model. This model properly calculates the transport of the turbulent shear stress and gives high accurate predictions. It can also predict on the amount of flow separation.

### 3.4.4 Combustion models

Combustion models in CFX use the same algorithm used for Multi-component Fluid with the addition of heat source/sink term due to chemical reactions. In CFX available combustion models are: i) Eddy dissipation model (EDM), ii) Finite rate chemistry (FRC) model, iii) Combined EDM/FRC, iv) Laminar flamelet (or Flamelet) model, and v) Burning velocity model.

The combustion rate is dominated by the rate of mixing of the materials. Due to the fact that the methane and air undergo fast reaction combustion, so the finite rate chemistry model is not a suitable model for the combustion in this particular case. The Combined EDM/FRC model has lot of similarity with the EDM and has no benefit over the EDM in this case. In fact, the convergence behavior of the Combined EDM/FRC model may be worse than that of the EDM according to ANSYS (2009).

The EDM, the Laminar flamelet model and the Burning velocity model are suitable for “fast” combustion modelling. The Burning velocity model is a part of the Flamelet model with some extra capability which is not considered here. So the extra capability of the Burning velocity model is not required and therefore it is sufficient to use the Flamelet model for this brick kiln simulation.
The EDM tracks each individual chemical component with its own transport equation. This model is flexible in a way that any new materials could be added. A limitation of this model is that intermediate species such as CO cannot be calculated with adequate accuracy. This may lead to over-prediction of flame temperature, usually in fuel-rich regions. The Flamelet model can simulate the products of incomplete combustion. For this reason it generally provides a more accurate solution than the EDM. However, one drawback of the Flamelet model is that it requires the availability of a Flamelet library for the required fuel/oxidizer combination over the pressure and temperature ranges of interest.

Fluid properties, including temperature and density, are computed from the mean composition of the fluid in the same way as for other combustion models, such as the EDM. In the Flamelet model, the effect of heat loss and pressure on density and temperature is taken into account.

**NO Model**

The NO model calculates mass fractions of NO formed in the combustion process. The NO formation model is fully integrated into the CFX reaction and combustion module. NO concentrations are typically very low and combustion is negligible. The NO is created or destroyed through four mechanisms: Thermal NO, Prompt NO, Fuel Nitrogen, and NO Re-burn. The fuel nitrogen mechanism only affects coal and oil combustion (Chacon et al. 2007). The Flamelet model utilizes post-processing in solving the concentration of NO. This post-processing can be coupled to the main solution so that the formulation of NO is driven by the main solution but is not going to affect the main solution. This approach is appropriate for the simulation because the mass fraction and reaction rate of NO are sufficiently small, so the effect on the main solution is negligible.

In the next chapter, how the above mentioned theories are appropriately utilized for analyzing the brick kiln environment using CFD is presented and then the optimized Tunnel kiln design is identified from CFD simulation.

### 3.5 Summary

ANSYS CFX is capable of modelling steady-state and transient flows, laminar and turbulent flows, heat transfer and thermal radiation, transport of non-reacting components, combustion, Particle tracking etc.
Meshing process in ANSYS meshing includes setting mesh method, specifying global mesh settings, inserting local mesh settings, preview and generating mesh and checking mesh quality. There are five meshing method in ANSYS Mesh for 3D geometries: Tetrahedrons, Sweep, Hex dominant, Multizone, and Automatic. The ways of controlling the mesh numbers and qualities include element size, global mesh controls, local mesh controls, advanced sizing functions, etc. Mesh quality can be checked by checking the orthogonal quality and skewness. CFX solver calculates 3 important measures of mesh quality at the start of a run and updates them each time the mesh is deformed - Mesh orthogonality, Aspect ratio, and Expansion factor.

Thermal energy option was selected to simulate the heat transfer in the domain. Radiation effect is considered when it is significant compared to convective and conductive heat transfer rates. Turbulence situation can be solved using the Standard k-ε model or Shear Stress Transport (SST) model, etc. For this research, P1 model is selected for radiation modelling and Standard k-ε model is selected for turbulence modelling and Flamelet model is selected as the combustion model. This model can simulate the products of incomplete combustion. For this reason it generally provides a more accurate solution than the Eddy Dissipation model (EDM). The NO formation model is integrated into the CFX reaction and combustion modules which provides complete solution to the NO model.
Chapter 4
CFD Simulation of Brick Kiln and Design Optimization

4.1 Evaluation of Brick Kiln Performance

Computational fluid dynamics (CFD) is becoming an important research tool in the field of combustion engineering. In recent years, CFD has been used increasingly to improve the efficiency in many industrial applications including combustion processes. With recent advancement of mathematical techniques and working of the computer with high performance hardware, CFD is found to be successful in simulating combustion. The CFD solutions are being used to increase efficiency and thus for optimization of design and reduction of emission from combustion by replacing expensive and time consuming experimentations.

Working with CFD involves six fundamental stages related to combustion processes: i) define model goal, ii) create model geometry and grid, iii) set up the solver and physical models, iv) compute and monitor the solutions, v) examine and save results, and vi) consider revisions to the numerical or physical models if necessary.

In the following sections and subsections, the modelling of the geometry, its meshing, selection of parameters and boundary conditions to simulate the processes and thereby optimization of the design is elaborated. The simulation clearly dictates towards a solution which is efficient in fuel consumption and reduced emission.

4.1.1 Tunnel kiln geometry

The dimensions of a typical Tunnel kiln geometry are given below based on industrial knowledge obtained from field visit and relevant literature (Oba et al. 2011; Chen et al. 1999). For modelling the Tunnel kiln geometry, the initial dimension as specified here is subjected to changes with simulation succession. The length and width of a typical Tunnel kiln geometry is taken as 100 m × 3.24 m as shown in Figure 4.1. This dimension is chosen from a space constraint point of view, which is going to remain unvarying in subsequent trials of other dimensional changes. As shown in Figure 4.1, green brick entrance is from the right end and finished fired brick exit is through the left end of the kiln. On the other hand, air flow entry direction is in the opposite direction of the brick moving direction. These brick and air
movement directions can be other way around. The height of the kiln is 1.48 m, which is also taken as another unvarying dimension. The initial height of the brick stack is taken as 1.38 m. A clearance of 100 mm is kept between the brick stack and the kiln roof, which is going to vary in simulations to get an idea about optimised clearance. The entry of the green brick zone is called the preheating zone, the exit of finished brick zone is called the cooling zone and the middle region is termed as firing zone as shown in Figure 4.1. Percentage of the length of preheating zone, firing zone and cooling zone of the brick kiln is taken based on Chen et al. (1999).

For combustion purpose 144 (12 rows × 12 columns) gas inlets are placed at a spacing of 1.32 m longitudinally and 225 mm laterally. These gas inlets are varied between 10 mm and 25 mm diameters. For complete combustion, ample air supply needs to reach the firing zone of the kiln. One large forced air inlet is necessary in this regard to supply and set the flow direction inside the kiln. For model simplification, air inlet is considered as rectangle. Cold air entering through this large air inlet extracts heat from the burnt bricks before reaching the firing zone. In order to have a better control over air temperature, some of this preheated air is extracted immediately after the large rectangular air inlet. This extracted heated air is transferred to the dryer to dry the green bricks. Hence, an intermediate size air outlet (opening) is placed as shown in Figure 4.1 to extract those preheated air from the kiln to the dryer. For this modelled geometry, large rectangular air inlet has an area of 1.5 m × 3.24 m whereas intermediate air outlet has an area of 0.75 m × 3.24 m. There is a gap of 4.74 m between the large air inlet and intermediate outlet. For fast cooling and extracting heat and have better control on temperature distribution in the fired bricks, some small air inlets and outlets (openings) are placed at alternate positions. A total of 156 (13 rows × 12 columns) air inlets and outlets are alternatively placed at a spacing of 1.32 m longitudinally and 20 mm laterally as shown in Figure 4.1. In these sets, 84 (7 × 12) are air inlets whereas 72 (6 × 12) are air outlets. A constant diameter of 250 mm for air inlets and outlets is considered for all the simulations. However, a varying velocity of air inlets is considered in those simulations. Finally at the other end of the kiln (near to the brick entry end), flue gas outlet needs to be placed to release burnt gases into the atmosphere. Flue gas outlet has an area of 1.5 m × 3.24 m in this geometry as shown in Figure 4.1.

Positioning of gas and air inlet-outlets at the gaps between two brick stacks or over the brick stacks directly can have four different combinations. In one combination, all the air and gas flows can be at the gaps between two brick stacks. In another two combinations air flows can be
on top of the bricks stack whereas gas flow can be in between two brick stacks or vice versa. In the fourth combination, all the air and gas flows can be over the brick stacks. Gas and air flows can be at different angles with respect to kiln roof. It varied between normal direction (90°) and 14° inclination with respect to kiln roof to see the impact on simulation.

As stated earlier, brick stack height is 1.38 m, while length and width are 920 mm and 440 mm, respectively. There are standard gaps of 100 mm between two brick stacks laterally and 400 mm longitudinally. A total of six brick stacks are placed side by side in the modelled Tunnel kiln laterally, whereas 75 brick stacks can be placed along the length of the kiln. It is to be noted that lateral placing of brick stacks is remained unvarying in the subsequent simulations, while longitudinal gap is varied between 200 and 400 mm. But total number of stacks kept 75 by varying the stack length between 920 mm and 1120 mm.

In order to reduce the computational time, the entire kiln geometry can be considered symmetric with respect to longitudinal centre line. However further close look into the geometry reveals that a longitudinal strip of 540 mm width is going to form six similar kiln strips. Each of these strips have 75 brick stacks longitudinally and one brick stack with 50 mm spaces on two sides (i.e. half of 100 mm lateral gaps) laterally. In some Tunnel kilns, side wall burners are present as well as roof top burners. For simplification of this simulation and to keep the symmetry of the geometry, only top burners are considered, no side wall burners are placed in the kiln. Total number of kiln cars inside the kiln is taken as 75, however in real life it may vary according to the actual length.

The burned gas from firing zone flows through the dry green bricks to preheat them and then released into the atmosphere by flue gas outlet. Though extraction of hot air is considered from intermediate and small air outlets before firing zone of the kiln to preheat green bricks in the dryer, this study is not focusing into the dryer environment.
Figure 4.1: Modelled Tunnel Kiln
4.1.2 Tunnel kiln curve

For any ceramic products, a temperature pattern needs to be maintained throughout the kiln to obtain a particular quality brick. This plot of temperature vs. distance is called the ‘Tunnel kiln curve’. Typically a Tunnel kiln curve shows the characteristic temperature distribution in space as shown in Figure 4.2 (Durakovic et al. 2006; Oba et al. 2011; Atanasov et al. 2007). Temperature is risen fast to 900°C after the entry of the green bricks. Then it remains stable for a short while and then rises again to the peak. The highest temperature that needs to be attained for ordinary bricks is around 1050°C for required vitrification of clays. In the cooling zone when the temperature is decreasing, it is kept stable at around 550-650°C for an appreciable distance, otherwise cracks may form. After a while, temperature inside the kiln is steadily decreased to room temperature at the exit. Temperature distribution inside the Tunnel kiln generated from the modelled design should closely match the Tunnel kiln curve found in literature as shown in Figure 4.2 for ordinary bricks. In this analysis, Tunnel kiln curve for various modelled designs are generated where different design parameters are applied. From those generated curves, the ones that closely match the theoretical curve is going to indicate the better set of design parameters.

Figure 4.2: Tunnel kiln curve for ordinary bricks; brick stack entry from the right
4.1.3 Building a model geometry

To set a model of a typical kiln/burner some simplification was assumed from the geometric perspective. Simplification was necessary to reduce the complexity of the geometry in order to simulate what is primarily happening inside the kiln. The geometry was successfully created by using pre-processor code ANSYS Design Modeller. The modelled strip length is considered to be 100 m long, 1.48 m height and 540 mm width. It is to be noted that width (i.e. laterally) of the brick stack is not going to vary but other dimensions, length and height is to vary to come up with an optimum dimension. In the modelled geometry drawn in ANSYS Design Modeller as shown in Figure 4.3, each of the brick stacks has a length of 920 mm, width of 540 mm and a height of 1.38 m. Kiln car height is considered included with the brick stack height. Spacing between brick stacks are 400 mm longitudinally. Laterally 50 mm spaces are considered on each sides of the brick stack. There is also 100 mm clearance between brick stack and the ceiling of the kiln. As one-sixth section along the entire length of the kiln was modelled, 12 rows × 2 columns gas inlets and 13 rows × 2 columns air inlets and outlets (openings) are drawn for the simulation of the entire kiln.

Figure 4.3: Schematic view of a Tunnel kiln modelled by ANSYS Design Modeller; brick stack entry from the right
4.1.4 Mesh generation

The volume of the selected kiln geometry is discretized into finite elements called “cells” using appropriate meshing tool, ANSYS Mesh. These cells are the fundamental units of calculation, as all the derived algebraic equations is to be solved at each node of these cells. After meshing, the generated nodes and elements are 104,184 and 101,526, respectively. Most of the elements are hexahedral type as shown in Figure 4.4. In hexahedral mesh, nodes are generated at equal distances giving quicker but accurate result. Local body sizing and face sizing are done to improve the number of nodes and elements. Figure 4.4 shows the distribution and quality of meshing generated by ANSYS Mesh.

![Figure 4.4: Distribution of mesh into the modelled section of the kiln (generated by ANSYS Mesh)](image)

Mesh independency analysis

Various types of meshes are generated in the kiln geometry to test its quality. Both orthogonal quality and skewness are found to be as desired as stated in Chapter 3. Models are run using various meshes and all other design and model parameters remained same. For mesh independency analysis, two different types of meshes are generated using Automatic and Hex dominant methods. Automatic meshes are generated using body size of 80 mm as shown in Figure 4.5 along with the corresponding simulated temperature distribution below. Body size of
80 mm means the distance between nodes generated in the geometry is roughly around 80 mm apart. In this method any type of mesh can be generated according to the shape of the geometry. Advanced size function selects ‘Proximity and Curvature’ and Relevance Centre selects ‘Coarse’

Figure 4.5: Automatic mesh using body sizing 80 mm (333,867 and 1,416,265 nodes and elements) and corresponding simulated temperature distribution curve

to generate around 333,867 and 1,416,265 nodes and elements respectively. On the other hand Hex dominant method is used to generate mesh as shown in Figure 4.6 where 100 mm body sizing is used for meshing. Face sizing of 80 mm in selected faces are also chosen. Nodes and elements generated using this method are around 106,406 and 105,208 respectively which is much lower than the Automatic method. However, the results on simulated temperature
distributions obtained from these two different simulations as shown in Figures 4.5 and 4.6 are found to be very much similar except in few places with bumps. Hence mesh independency of the two modelled geometry is clearly visible.

Figure 4.6: Hex dominant mesh using body sizing 100 mm (106,406 and 105,208 nodes and elements) and corresponding simulated temperature distribution curve

4.1.5 Simulation parameters and boundary conditions

After generating the meshes in ANSYS Mesh, all the boundary conditions have to be defined using CFX Pre. To start the simulation, the velocities of the fuel (gas) and air entering into the kiln are required to model the process. Gas and air inlet temperatures need to be defined at the beginning; mass fractions of different components of gas and air need to be provided at the start
of the simulation. It is assumed that the supplied air is consisted of 23.2% oxygen and rest is nitrogen. These proportions of oxygen and nitrogen can be considered for the reactions inside the model domain. Combustion models require a small fraction of reaction products (CO\textsubscript{2} and H\textsubscript{2}O) to be given at the inlet to initiate combustion simulation. Hence, 0.01 mass fractions of CO\textsubscript{2} and H\textsubscript{2}O are required at the inlet for proper starting of the reaction simulation (ANSYS 2009).

The default boundary for any undefined surface in CFX-Pre is considered as no-slip, smooth, adiabatic wall. The walls of the kiln are also assumed to be adiabatic. It is considered that gas nozzle opening is in the same plane as the kiln roof. For radiation purpose, the wall is assumed to be perfectly absorbing and emitting surface (emissivity = 1). The kiln wall is non-catalytic, which means, it is not taking part in the chemical reaction. Probable temperatures of the different brick stacks are also defined to initiate the model simulation. Brick stack near the entry has lower temperature and as it moves near the firing zone, the temperature increases. Opposite trend is shown as the brick stack moves from firing zone to the exit. Heat transfer coefficient for the brick stack is given as 10 W/m\textsuperscript{2}K as identified in Meng (2011). Gas inlet temperature is assigned as 150\textdegree C. The velocity of incoming gas is given as 6 m/s. Air inlet velocity is taken as around 0.83 m/s at an angle of 14\textdegree. It is to be noted here that these values on air and gas velocities are obtained after several trial runs.

4.1.6 Turbulence, radiation, combustion and NO models

The models that have been applied for the simulation of the brick kiln are: Turbulence model (Standard $k-\varepsilon$), Radiation model (P-1), and Combustion model (Flamelet). As high temperature combustion occurs inside the Tunnel kiln, turbulence is generated. To simulate this turbulence properly Turbulence model is necessary. Combustion model is added to simulate the generation of CO\textsubscript{2}. Separate NO model has to be added to simulate the generation of NO emission. As high temperature is generated inside the kiln, radiation heat transfer also becomes significant; hence a Radiation model is also incorporated as mentioned above.

The Standard $k-\varepsilon$ model in CFX is one of the simplest complete models of turbulence, in which the solution of the transport equations are independently determined (Chacon et al. 2007). Radiative heat transfer is included because the radiant heat flux is high and should be considered along with convection and conduction considered in Combustion model. CFX includes Combustion models to allow the simulation of flows in which combustion reactions occur. The
Flamelet was developed for use in a wide range of turbulent reaction flows. Because of its simplicity and robust performance in predicting turbulent reaction flows, this model has been widely applied in the prediction of industrial flames (Chacon et.al 2007). In CFX, the NO model is solved in a separate equation. To model NO, the reaction scheme Methane Air WD1 NO PDF is selected. This introduces NO as an additional component and adds reactions for Thermal and Prompt NO models (ANSYS 2009).

4.2 Simulation using ANSYS CFX

In order to initiate a CFD simulation in brick kiln, the assumptions made for the model are that the process is under steady-state condition - the temperature at any point remains constant with time. Due to symmetry assumption, all the strips can replicate this modelled strip and thus can provide idea of the entire Tunnel kiln geometry.

The simulation is run for steady-state condition, where convergence criterion with RMS (root mean square) value is taken as $10^{-4}$. A suite of trial and error runs show that 600 iterations are adequate to obtain a fairly stable solution. However it is imperative that, if more iteration is given the result would marginally improve. From CFX-Post, temperature profile as well as CO$_2$ and NO emission profiles are obtained. Temperature distribution and simulated temperature distribution curve generated are shown in Figures 4.7 and 4.8. Figure 4.7 shows the temperature distribution inside the Tunnel kiln when gas velocity is 6 m/s (gas flow rate 0.071 m$^3$/s). Figure 4.8 on simulated temperature distribution matches closely with the Tunnel kiln curve obtained from industry and literature (Durakovic et al. 2006; Oba et al. 2011; Atanasov et al. 2007), which indicates that simulation has progressed in the right direction. It is to be noted that the simulation showed in Figures 4.7 and 4.8 are based on 400 mm spacing between brick stacks and the gas and air inlet-outlets positions are in between these two brick stacks. However some modifications on model geometry and design parameters are carried out to improve the performance of the Tunnel kiln further.

Figure 4.7 clearly distinguishes the firing, cooling and pre-heating zones. The highest temperature generated is found to be about 1050°C in the firing zone and the lowest temperature is 50°C at the exit of the finished brick. Figure 4.9 shows the high CO$_2$ concentration after the firing zone, which moves right and upward due to overall flow direction and temperature rise. This heated flow increases the brick temperature to attain a maximum temperature of 1050°C and
continue steadily for a while in the downward direction. The mass fraction (i.e. ratio between mass of the gas to the total mass of the gases inside the kiln) of CO₂ generated near the firing zone ranges from 0.05 to 0.174 which when estimated for the whole volume of the kiln strip, a rate of 1.01 m³/s flow is generated inside the strip. Simulated concentration of NO is also shown in Figure 4.10. The mass fraction of NO generated inside the kiln near the firing zone is in the range of 0.005 to 0.01 which when similarly estimated for the whole volume of the kiln strip, a rate of 0.108 m³/s flow is generated inside the strip. As the volume of CO₂ generated inside the kiln largely depends on the highest temperature reached by the kiln, the theoretical calculation of CO₂ generated can also be included here to give a better picture on emission. Theoretically 0.028 kg/s CO₂ is generated inside the kiln strip for 0.071 m³/s gas flow rate. The amount of CO₂ generated per 100,000 bricks is 26.22 tCO₂e as calculated in Appendix A.

Figure 4.7: Temperature distribution inside the brick kiln (sectional view)

Figure 4.8: Temperature distribution inside the brick kiln for 6 m/s gas velocity (gas flow rate 0.071 m³/s)
The simulated gaseous velocity vectors inside the tunnel are also identified in Figures 4.11, 4.12 and 4.13 at cooling, firing and preheating zones respectively. In the cooling zone, velocity vector shows entry of cooling air at 14° angle inside the kiln where some of this air after extracting heat from the brick stack is flown to the dryer through intermediate air outlet. Gaseous velocity near the firing zone is very high due to combustion as shown in Figure 4.12. After the combustion, as the temperature gradually decreases towards the preheating zone, air velocity reduces as a consequence and finally flows out through the flue gas outlet as shown in Figure 4.13.
4.3 Optimizing the Design of the Tunnel Kiln

4.3.1 Gas flow rate

Gas velocity

In the modelled geometry, 12×2 gas inlets are taken with a diameter of 25 mm each. It is found from the simulation (as shown in Figure 4.14) that if the gas velocity is about 15 m/s (0.177 m³/s
gas flow rate) it causes gas to accumulate on two sides of the firing zone, as a result temperature rise is much higher at the end of preheating zone and at the beginning of cooling zone and relatively less temperature in firing zone. It is clear from the simulation that the temperature distribution is not matching the industrial Tunnel kiln curve. However if the gas velocity is kept on decreasing, it shows that at 6 m/s velocity the simulated temperature distribution (as shown in Figure 4.8) matches closely to the industrial Tunnel kiln curve. To have a good idea on simulated temperature distributions at 5 m/s and 4 m/s are also shown in Figures 4.15 and 4.16 respectively.

Figure 4.14: Temperature distribution generated for 15 m/s gas flow velocity (0.177 m$^3$/s gas flow rate)

Reducing gas velocity to 5 m/s (0.059 m$^3$/s gas flow rate) as shown in Figure 4.15 exhibits that temperature distribution is becoming steeper than desired in the preheating and cooling zone. And in the firing zone, the temperature suddenly peaks and then drops quickly instead of remaining stable for a considerable distance. Gas velocity of 4 m/s (0.047 m$^3$/s gas flow rate) as shown in Figure 4.16 also shows similar trend. From this analysis, the optimum gas velocity is found to be 6 m/s. However, it is to be noted that there is marginal difference exists for temperature distribution between the gas velocities 5 m/s and 6 m/s. If the gas velocity is 5 m/s then the curve shape still remains acceptable, however the curve remains in the high temperature zone for a short distance as the temperature rises and then falls quickly. So, quality of bricks produced using this temperature distribution is be slightly inferior. However, energy
consumption and emission are going to reduce as the gas flow rate reduces. So if slight quality deterioration is acceptable then gas inlet velocity of 5 m/s can also be a better choice. However for all other analysis of this research, the optimum gas velocity is considered 6 m/s. Reduction of gas velocity means less fuel flow rate and as a result less carbon-di-oxide to generate. Theoretically 0.0238 kg/s and 0.019 kg/s CO₂ is generated inside the kiln for the respective flow rates.

Figure 4.15: Temperature distribution generated for 5 m/s gas flow velocity (0.059 m³/s gas flow rate)

Figure 4.16: Temperature distribution for 4 m/s gas flow velocity (0.047 m³/s gas flow rate)
Gas inlet diameter

A comparable trend is seen if the gas velocity remains constant and the diameter of the gas inlet is changed. Reduction of the inlet diameter causes reduced flow rate, which generates a peak temperature of around 1200°C to produce even steeper curve in preheating and cooling zones than desired. The curve becomes steeper as it quickly reaches the peak and then falls quickly as shown in Figures 4.17 and 4.18 for 15 mm (gas flow rate of 0.025 m³/s) and 10 mm (gas flow rate of 0.011 m³/s) diameters respectively at 6 m/s velocity. Reduction of gas inlet diameter also causes less CO₂ productions as less fuel is burnt. For these two cases, theoretical CO₂ generated is 0.01 kg/s and 0.0044 kg/s respectively.

If the gas flow rate remains constant at 0.071 m³/s and the corresponding velocity is increased to 16.51 m/s and 37.69 m/s for reduced diameters of 15 mm and 10 mm respectively, it generates again steeper temperature distribution curves (as shown in Figures 4.19 and 4.20) compared to 6 m/s velocity with 25 mm diameter inlet design.

The graphs clearly show that when the gas inlet diameters are reduced gradually (velocity 6 m/s), flow becomes concentrated while taking part in the reaction and thus increase the peak temperature. However the spread of the high temperature zone reduces, i.e. temperature distribution becomes steeper on two sides. Again when the gas inlet diameter is reduced but the velocity is increased to maintain constant flow rate (0.071 m³/s) then the peak temperature also increases while the spread of the high temperature zones remain less steep than the previous case of reduced diameter and constant velocity. Here it is a matter of balance between the choice of diameter and velocity of gas. It is obvious that while the velocity is 6 m/s with a inlet diameter of 25 mm the resultant simulated temperature distribution is closer to the industrial Tunnel kiln curve.
Figure 4.17: Temperature distribution generated of gas inlet diameter 15 mm (flow rate 0.025 m³/s)

Figure 4.18: Temperature distribution generated of gas inlet diameter 10 mm (flow rate 0.011 m³/s)
4.3.2 Gas velocity direction

In previous simulations, gas velocity direction was vertically downward through the gas nozzles. So after entering the kiln, gas hits the kiln bottom or brick stacks and then dispersed in both longitudinal directions as shown in Figure 4.21. Velocity vectors as shown in Figure 4.22 presents that some hot gaseous flow from the combustion zone is moving opposite to the
intended flow direction (towards flue gas outlet) and reaching as far as the small air outlets and passes to the dryer. This phenomenon is not desirable as CO$_2$ and other flue gases generated should be flowing towards the flue gas outlet where a purifier is usually attached. The purpose of this purifier is to remove particulate emissions before releasing through the flue gas outlet into the atmosphere.

![Figure 4.21: Gaseous velocity vectors near the firing zone in vertical planes](image)

Figure 4.21: Gaseous velocity vectors near the firing zone in vertical planes

![Figure 4.22: Gaseous velocity vectors near the firing zone in horizontal planes](image)

Figure 4.22: Gaseous velocity vectors near the firing zone in horizontal planes
To minimize the effect of backflow of hot gas flow in the firing zone, gas burners are placed at an angle so the gas enters the firing zone at 45°. Inclined 45° gas flow inside the firing chamber may drive the hot gas towards the flue gas outlet instead of small air outlets in the opposite direction. As shown in Figure 4.23, gas inlet is placed at an angle so that gas and air flows are only diverted towards the flue gas outlet direction. Though backflow of the hot gas towards the small air outlet could not be totally stopped, however this change ensures a small quantity hot gas flowing in the opposite direction towards the small air outlet. Figure 4.23 is the gas flow direction at 45° while inlet velocity of the two left-side gas inlets are reduced to 1 m/s which shows significantly less hot gas flow in the direction of small air outlets as shown in Figure 4.24 compared to Figures 4.21 and 4.22.

![Figure 4.23: Gas flow in the firing zone at 45° angle](image)

![Figure 4.24: Hot gas flow direction near small air outlets when gas inflow direction is at 45° angle](image)

The temperature distribution curve for gas inlet at an angle of 45° in Figure 4.25 shows some fluctuations in the preheating zone. Gas entering the firing zone creates accumulation of more hot gases in the preheating zone, resulting into temperature spike in the temperature profile. Other angles between 90° and 45° are also tried and it is found that in all the cases some spikes remain visible and it is never possible to reduce the backflow of hot gases completely. So the direction of gas flow could be kept normal to the kiln roof and some backflow of hot gases towards small air outlets has to be accepted.
Figure 4.25: Temperature spike in preheating zone generated due to gas flow angle at 45°

4.3.3 Air velocity

At the exit end of the finished brick, air entry direction was perpendicular to the kiln roof. Simulated result clearly showed in Figure 4.26 that backflow of air through the same inlet was significant which was due to direct hitting of the air to the brick stack.

Figure 4.26: Velocity vectors when air flow direction through large air inlet is normal to kiln roof

To reduce this backflow, different angles of airflows are applied. Figure 4.27 shows airflow direction at 14° with respect to the kiln roof. This airflow angle showed better performance as no backflow is visible through large air inlet. Immediately after the entry, uniform flow is visible through the kiln with some heated air coming out through the intermediate air outlet due to
natural convection. This heated air is transferred to dryer to reduce the moisture of the green bricks. The amount of heated air coming out of intermediate air outlet and small air outlets are

simulated to be about 6.83 kJ/s as calculated in Eq A.1 of Appendix A. However after reaching the firing zone due to addition of combustible gas, fluid flow velocity increased significantly in the region as shown in Figure 4.28. Eventually flow velocity again decreased at the entry of the green bricks near to the flue gas outlet as shown in Figure 4.29.
Figure 4.28 Gaseous flow directions near firing zone

Figure 4.29: Gaseous flow direction in vertical and horizontal planes near flue gas outlet
4.3.4 Gaps between brick stack and kiln roof

50 mm gap

When the gap between the top of the brick stack and the roof is reduced to 50 mm, bricks placed on the upper portion of the stack face more temperature fluctuation due to the incoming cooling air. As a result of this fluctuation, necessary structural change may be hampered and cracks may be formed (Personal Communication 2012). The evidence of this fluctuation is presented in Figure 4.30. From this analysis, it can be concluded that, increasing the brick stack height or reducing the gap between the stack and kiln roof increases temperature fluctuation. This may eventually deteriorate the uniform quality of the bricks on the top of the stack.

Figure 4.30: Temperature distribution when gap between the top of the brick stack and the roof is reduced to 50 mm
**200 mm gap**

Increasing the gap between the brick stack and the kiln roof to 200 mm shows less temperature fluctuation compared to the gap of 50 mm as shown in Figure 4.31. The fluctuation is even less compared to the earlier 100 mm gap as shown in Figure 4.8.

![Figure 4.31: Temperature distribution when gap between the top of the brick stack and the roof is increased to 200 mm](image)

From the comparison, it can be said that, if the brick stack gap is doubled from 100 mm to 200 mm, it generates a better Tunnel kiln curve so ensures quality brick production. However, the gap between kiln roof and the brick stack is not increased further because some of the initial simulations showed that if the gap between brick stack and the kiln roof is too large, then
gaseous flow does not enter the stack properly, rather it free flows through the top gap and thereby would waste considerable heat energy. Also the volume of bricks in each batch also decreases for a corresponding increase of energy requirement.

4.3.5 Positioning brick stacks with respect to gas and air openings

As stated earlier a combination of four cases is considered under this category of simulations. In all those cases as shown in Figures 4.32 to 4.35, a roof gap of 200 mm is maintained in all the simulations.

Case 1: Brick stacks positioned in the middle of two air inlet-outlets and gas inlets

For this brick stack positioning, the generated temperature curves are fluctuating near the air inlet-outlets and gas inlet positions as shown in Figure 4.32.
Case 2: Brick stacks positioned in the middle of two air inlet-outlets and directly below the gas inlets

For this case the temperature curve shows relatively smooth change in the gas inlet position, while some fluctuations are visible in the air inlet and outlet positions as shown in Figure 4.33. So, a decision can be drawn that, if brick stacks are positioned directly below the gas inlet then a smooth curve can be obtained near gas inlet region. Smooth curve ensures less temperature fluctuations and thus uniform quality bricks.

Case 3: Brick stacks positioned just below air inlet-outlets or in between two gas inlets

For this case the temperature curve shows relatively smooth change in the air inlet-outlet positions however some fluctuation in the gas inlet positions as shown in Figure 4.34. Though slight fluctuations is not going to cause huge quality difference however, smooth curve may
ensure good quality bricks. So, a decision can be drawn that, if brick stacks are positioned directly below the air inlet-outlets then a smooth curve can be obtained near the air inlet-outlet region.

Figure 4.34: Temperature distribution generated for brick stack positioned directly below the air inlet-outlets and in between two gas inlets

Case 4: Brick stacks positioned directly below air inlet-outlets or gas inlets

Finally, for this case the temperature distribution curve shows relatively smooth change near the air inlet-outlet positions and gas inlet positions as shown in Figure 4.35. Thus, conclusion can be drawn that this Case 4 is the most suitable brick stack positioning configuration to manufacture uniform quality bricks.
4.3.6 Gap between brick stacks

**Brick stacks gap reduced to 300 mm and stack length increased to 1020 mm**

Gap reduction between two brick stacks ensures higher brick production as more bricks can be accommodated at a given batch inside the kiln. In Figure 4.36, the gap between the stacks is reduced to 300 mm and as a consequence the stack length has increased to 1020 mm. The generated temperature distribution curve with this configuration shows a smooth pattern.
Brick stacks gap reduced to 200 mm and stack length increased to 1120 mm

Further decrease of brick stack gaps to 200 mm and consequently increase of brick stack lengths to 1120 mm more or less retains the smoothness of temperature distribution of the previous case as shown in Figure 4.37. Without increasing the brick stack size, the gaps between the brick stacks could be reduced to increase the number of brick stacks beyond 75. Increasing the brick stack size or the stack number increases the brick production by accommodating more bricks at the same batch inside the kiln. However, the fuel usage remains the same and thus the production becomes more fuel efficient. A further reduction of gaps showed increased fluctuation in the temperature distribution curve because small air inlet-outlet diameters are taken 250 mm, so a further reduction in the stack gap is not bound to bring better result. So there should be a balance between gap and quality of the brick production.
From this simulation, it can be concluded that, brick stack gaps could be reduced to 200 mm. However, stack width may remain same. In that way the number of brick stacks is going to be increased. More bricks can be produced with the same amount of fuel and thus the efficiency of the kiln can be improved.

**4.3.7 Efficient geometric model prediction from simulation**

From all the simulations above, optimum gas velocity is found to be 6 m/s with gas inlet diameter of 25 mm to produce a desired temperature distribution matching the industrial Tunnel kiln curve. Backflow of hot gas in the opposite direction of intended flow is a problem. This problem is tried to be solved by placing the gas inlet at an angle of 45°. Even though the backward flow of hot gas is reduced as an effect of this angled flow, the fluctuation in the generated temperature distribution curve has increased. So, for the sake of producing better temperature distribution curve, backflow of a portion of the hot gas has been taken acceptable.
From the simulation it is found that 200 mm gap between brick stacks and kiln roof ensures better temperature distribution along the kiln length. So the gap between brick stacks and kiln roof can be increased to 200 mm compared to 100 mm as initial guess. If brick stacks are positioned just below air inlet-outlets or gas inlets then temperature distribution curve achieves desired characteristics better. Reducing the gaps between brick stacks produces better temperature distribution curve. The gaps between the brick stacks can be reduced to 200 mm. However, the length of the brick stacks may remain 920 mm. As a result, more brick stacks can be accommodated at a given batch inside the brick kiln. This is going to ensure higher brick production for the same fuel consumption. The Tunnel kiln dimensions as optimized through all the above systematic runs of the model can be shown in Figure 4.38. To show the impact of all those designed parameters are summarized in Table 4.1 for easy comparison.
Figure 438: Dimensions of proposed Tunnel kiln
<table>
<thead>
<tr>
<th>No.</th>
<th>Design parameter</th>
<th>Design parameter variation</th>
<th>Result/Impact</th>
<th>Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gas flow rate</td>
<td>Velocity 15 m/s, diameter 25 mm</td>
<td>Gas accumulates on both side of the firing zone</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity 6 m/s, diameter 25 mm</td>
<td>Optimum Tunnel kiln curve generated</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity 4 and 5 m/s, diameter 25 mm</td>
<td>Temperature distribution curve steeper than desired. Though 5m/s velocity can be accepted if slightly inferior quality brick is accepted</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity 6 m/s, diameter 10 and 15 mm</td>
<td>Temperature distribution curve steeper than desired</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity 16.51 m/s, diameter 15 mm</td>
<td>Fluctuation in curve</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity 37.69 m/s, diameter 10 mm</td>
<td>Fluctuation in curve</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td>Gas velocity direction</td>
<td>Normal</td>
<td>Some hot gas flowing in opposite direction of airflow</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At an angle</td>
<td>Tunnel kiln curve affected due to angled gas flow</td>
<td>×</td>
</tr>
<tr>
<td>3</td>
<td>Air velocity direction through large air inlet</td>
<td>Normal</td>
<td>Causes backflow through same air inlet</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At an angle</td>
<td>Air flow is uniform inside the kiln. 14° is optimum</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Gap between brick stack and kiln roof</td>
<td>50 mm</td>
<td>Temperature fluctuates along the length of the kiln</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 mm</td>
<td>Less fluctuation in temperature compared to 50 mm gap</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 mm</td>
<td>Smooth temperature distribution obtained</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>Position of brick stack wrt gas inlet</td>
<td>Brick stack in between two gas inlets</td>
<td>Fluctuation in temperature distribution curve</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brick stack directly below gas inlets</td>
<td>Relatively smooth curve</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brick stack in between two air inlet-outlets</td>
<td>Fluctuation in temperature curve</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brick stack directly below air inlet-outlets</td>
<td>Relatively smooth curve</td>
<td>✓</td>
</tr>
</tbody>
</table>
### 4.4 Summary

For simulation purpose, the geometry of a typical Tunnel kiln is drawn using ANSYS Design Modeller. Due to symmetry, one-sixth of the width (540 mm) along the entire length (100 m) of the kiln is considered adequate for simulation. The volume of the selected kiln geometry is discretized using ANSYS Mesh. Boundary conditions are defined using CFX Pre. Mesh independency analysis is conducted using two meshing methods and is found to be ‘mesh independent’. Proper models for turbulence, combustion and radiation are selected and the simulation is run under steady-state condition.

If the gas velocity is more than 6 m/s, it causes gas to accumulate on both sides of the firing zone. Gas velocity of 6 m/s with gas inlet diameter of 25 mm generates a better temperature distribution curve to match industrial Tunnel kiln curve. Keeping the gas velocity constant and reducing the gas inlet diameter as well as keeping gas inlet diameter constant and reducing the gas velocity, generates steeper temperature distribution curves as gas flow rate has been reduced in both the cases. Gas inlet velocity of 5 m/s with 25 mm gas inlet diameter can also be accepted if slightly inferior quality bricks are accepted. If the quality of the outputs from the Tunnel kiln is slightly compromised then the fuel consumption is going to be significantly reduce and thus is going to reduce emission further. It is found from the simulation that, lower gas inflow into the combustion chamber results less emission. So, reducing gas flow rate is going to reduce CO₂ and NO production. So, the modified design may ensure less pollution.

To reduce hot gas flow in the opposite direction of the intended airflow, attempts are made to place the gas inlet direction at an angle. However, this initiative affects the generation of temperature distribution curve and thus not considered for further simulation. Gas inflow direction is thus kept normal to kiln roof. Reduction of the gap between brick stacks and kiln roof causes more fluctuation in temperature distribution to impact uniform burning of the bricks. On the other hand if air flow direction from the large air inlet is normal to the kiln roof then due
to direct strike on brick stack or kiln bottom, some backflow is inevitable. Air inflow at an angle of 14° to kiln roof ensures uniform flow through the kiln.

The optimum gap between brick stacks and kiln roof is thus taken to be 200 mm. If brick stacks are placed in between two air inlet-outlets and/or gas inlets then the temperature curve becomes fluctuating. However, if brick stacks are positioned directly below the air inlet-outlets and gas inlets, relatively smooth temperature distribution can be obtained and thus adopted as optimum design parameter. Reduction of the gap between brick stacks ensures higher brick production as more bricks can be accommodated at the same batch inside the kiln. If the gap between the stacks is reduced to 200 mm, it retains the smoothness of the curve.
Chapter 5
Conclusion and Recommendation

5.1 Conclusion

This study demonstrated that CFD can be used as an effective tool for analysis and design for brick burning application. The CFD simulations are being used to increase efficiency and thus optimize the design and reduce emissions of combustion by replacing expensive and time consuming experiments. Commercially available software ANSYS CFX is used to evaluate temperature profile and CO\textsubscript{x} and NO\textsubscript{x} emissions in the system.

After drawing, meshing and simulating the Tunnel kiln geometry, generated temperature distribution curve from the simulation is verified against Tunnel kiln curve obtained from industry. Several model runs with changing parameters are carried out systematically to obtain an idea about best possible performance of a given Tunnel kiln. The resultant best performing parameters are setting an optimized design in order to improve the performance of the kiln. For design optimization several simulations are run by altering the design conditions and thereby simultaneously CO\textsubscript{x} and NO\textsubscript{x} emissions from various designs are compared and a low emitting design is obtained.

In the optimized simulation the highest temperature obtained is around 1050°C and the lowest temperature during the exit of the finished brick is around 50°C. It is found from the simulation that at gas velocity of 6 m/s through an inlet diameter of 25 mm, the temperature distribution curve obtained closely matches the industrial Tunnel kiln curve. Gas inlet can be placed at an angle so that gaseous flow is only directed towards the flue gas outlet and thus backflow of heated gas can be minimized. However, angled gas flow causes fluctuation in the temperature distribution curve. So, gas flow direction normal to the kiln roof is found to be more effective. If the gap between brick stack and kiln roof is increased to 200 mm, the temperature fluctuation in the Tunnel kiln curve is reduced compared to the initial gap of 100 mm. Hence, a gap of 200 mm between brick stacks and kiln roof is proposed for modified design. If brick stacks are placed just below the air inlet-outlets and gas inlets, then better temperature distribution curve is obtained.
Suggestions are made to reduce the gap between brick stacks to 200 mm from the initial 400 mm gaps, without increasing the brick stack size but by increasing the number of brick stacks. As a result a further smoother temperature distribution is obtained. This particular arrangement is going to increase the brick production with the same amount of fuel consumed and thus make the production more fuel efficient. Larger inlet air flow direction is set to 14° to ensure uniform gaseous flow through the kiln towards flue gas outlet.

It is found from the simulation that lesser gas inflow in the combustion chamber results less CO\textsubscript{2} and NO generation. So, reducing the gas inlet velocity or gas inlet diameter can definitely reduce CO\textsubscript{2} and NO production. So, the modified design ensures less pollution. The amount of CO\textsubscript{2} generated per 100,000 bricks from the proposed Tunnel kiln design is 26.22 tCO\textsubscript{2}e. Though this amount is equivalent to the low efficiency kilns as found from Chapter 5, however, it is to be noted that the quality of bricks generated from the Tunnel kiln is far superior compared to the bricks produced in those inefficient kilns. Bricks produced from Tunnel kilns are superior in strength, color and quality so requires more energy. So, it can be concluded that even same amount of energy is used in Tunnel kilns however this energy is efficiently utilized to produce superior quality bricks. If the quality of the outputs from the Tunnel kiln is slightly compromised then the fuel consumption is going to be significantly reduced and thus can reduce emission further.

5.2 Recommendation

High concentration of fluoride in clay minerals of Australia have a considerable impact on its emission (Environment Protection Authority 1999), so fluoride emission simulation can be incorporated in the future by adding user defined function (UDF) in the model. Only Tunnel kiln based on gas firing was simulated, however currently in many countries coal fired Tunnel, Hoffman, Vertical Shaft and Zigzag kilns are in use. CFD simulation can be conducted in those kilns as well to improve their performances. So coal based kilns can be simulated using ANSYS CFX to determine comparative emission performances.
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Appendix A

1 mol of CH$_4$ generates 1 mol (44 grams) of CO$_2$.

At firing zone temperature and pressure, 1 mol of CH$_4$ has a volume of 0.109 m$^3$ \[ V = \frac{RT}{P} \]

From 144 (12×12) gas inlets with 25 mm diameter and a velocity of 6 m/s, total flow rate is 0.42 m$^3$ of CH$_4$. From this amount of methane 0.17 kg/s of CO$_2$ should generate theoretically. So, if the Tunnel kiln is run for 365 days of a year, the amount of CO$_2$ generated is 5346 ton.

Volume of total brick stack at a time inside the kiln is 251 m$^3$ (Length 0.92 mm × Width 0.44 mm × Height 1.38 mm × 75 rows × 6 columns). Volume of one brick is 2.25 m$^3$. Brick numbers at a time inside the kiln is 111725. If it is assumed that brick stack remains inside the tunnel for 2 days, then total brick numbers burnt inside the kiln for the whole year are 20,389,711. So, the amount of CO$_2$ generated per 100,000 bricks is 26.22 tCO$_2$e.

At the firing zone temperature and pressure, 0.109 m$^3$ of CH$_4$ generates 44 gram of CO$_2$. So,

0.07 m$^3$ of CH$_4$ generates (.044×.07/0.109) = 0.028 kg/s of CO$_2$

0.059 m$^3$ of CH$_4$ generates (.044×.059/0.109) = 0.0238 kg/s of CO$_2$

0.047 m$^3$ of CH$_4$ generates (.044×.049/0.109) = 0.019 kg/s of CO$_2$

0.025 m$^3$ of CH$_4$ generates (.044×.025/0.109) = 0.01 kg/s of CO$_2$

0.011 m$^3$ of CH$_4$ generates (.044×.011/0.109) = 0.004 kg/s of CO$_2$

Heat energy released from the intermediate air outlet to the dryer can be calculated using the following formula:

\[ Q = m \cdot C_p \cdot \Delta \theta \] (A.1)

Here \( m \) is found from the simulated result as 0.158 kg/s, \( C_p \) is 1.006 for air and air inlet temperature is 25°C whereas average temperature at intermediate air is found to be 68°C. So, the temperature difference \( \Delta \theta \) is 43°C.

So, energy transfer for intermediate air outlet is 6.83 kJ/s.

Calculation for Emission of HK, VSBK, FCK and Zigzag kiln (CDM 2007; Environment Australia 1998)
\[ E = SFC \times Q \times EF \times CF \]  

(B.5)

where \( E \) = emission of CO\(_2\) in tCO\(_2\)e, \( SFC \) = specific fuel (energy) consumption in the kiln (TJ/brick), \( Q \) = total number of brick production in question (say, 100,000 bricks), \( EF \) = IPCC default carbon emission factor for the given fuel (in this case, coal) = 25.80 tC/TJ, \( CF \) = carbon to CO\(_2\) conversion factor = 3.67 tCO\(_2\)e/tC (CDM 2007).

The specific fuel (energy) consumption, \( SFC \) (TJ/brick) can be calculated as follows:

\[ SFC = \frac{Q_{\text{coal}} \times CV_{\text{coal}}}{Q_{\text{brick}}} \]  

(B.6)

where \( Q_{\text{coal}} \) = total coal consumption per 100,000 bricks for the given kiln, \( CV_{\text{coal}} \) = calorific value of the coal (16,748 KJ/kg coal) (CDM 2007), \( Q_{\text{bricks}} \) = number of bricks produced (say, 100,000 bricks).

\[
SFC_{\text{FCK}} = \frac{24,000 \text{ kg} \times 16,748 \text{ KJ/kg}}{100,000} = 4019.5 \text{ KJ/brick} = 4.02 \times 10^{-6} \text{ TJ/brick}
\]

\[
SFC_{\text{HHK}} = \frac{14,000 \text{ kg} \times 16,748 \text{ KJ/kg}}{100,000} = 2344.7 \text{ KJ/brick} = 2.35 \times 10^{-6} \text{ TJ/brick}
\]

\[
SFC_{\text{VSBR}} = \frac{10,000 \text{ kg} \times 16,748 \text{ KJ/kg}}{100,000} = 1674.8 \text{ KJ/brick} = 1.68 \times 10^{-6} \text{ TJ/brick}
\]

\[
SFC_{\text{ZigZag}} = \frac{18,000 \text{ kg} \times 16,748 \text{ KJ/kg}}{100,000} = 3014.6 \text{ KJ/brick} = 3.02 \times 10^{-6} \text{ TJ/brick}
\]

Emission of CO\(_2\) in tCO\(_2\)e per 100,000 brick production in each type of kiln

\[
E_{\text{FCK}} = 4.02 \times 10^{-6} \text{ TJ/brick} \times 100,000 \text{ bricks} \times 25.8 \text{ tC/TJ} \times 3.67 \text{ tCO}_2\text{e/tC} = 38.06 \text{ tCO}_2\text{e}
\]

\[
E_{\text{HHK}} = 2.35 \times 10^{-6} \text{ TJ/brick} \times 100,000 \text{ bricks} \times 25.8 \text{ tC/TJ} \times 3.67 \text{ tCO}_2\text{e/tC} = 22.20 \text{ tCO}_2\text{e}
\]

\[
E_{\text{VSBR}} = 1.68 \times 10^{-6} \text{ TJ/brick} \times 100,000 \text{ bricks} \times 25.8 \text{ tC/TJ} \times 3.67 \text{ tCO}_2\text{e/tC} = 15.86 \text{ tCO}_2\text{e}
\]

\[
E_{\text{ZigZag}} = 3.02 \times 10^{-6} \text{ TJ/brick} \times 100,000 \text{ bricks} \times 25.8 \text{ tC/TJ} \times 3.67 \text{ tCO}_2\text{e/tC} = 28.54 \text{ tCO}_2\text{e}
\]
Appendix B
