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Efficiency of a Wood-Fired Bakery Oven – Improvement by Theoretical and Practical

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover: Local temperature profile of the all surfaces of the wood-fired bakery oven

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Abstract

Combustion of biomass in small-scale furnaces is widely used in many countries and in different applications. The technology used is often "fixed grate" combustion in small batch furnaces. The efficiency of such furnaces is often low, which results in high environmental impact due to the poorly controlled combustion of the wood logs that are largely used as the heat source for baking bread in wood-fired bakery ovens. This work has been undertaken in order to develop an efficient and environmentally friendly bakery oven furnace fired by biomass. The work was performed in Mozambique, and a survey was used to evaluate the consumption of wood and the technology used in the process of bread baking in two selected townships. The data collected from the 104 bakeries consisted of the dimensions of the oven, the temperature profiles of the combustion chamber and baking oven, the baking time and the bread quality.

The circulation of hot gases within a baking oven was used to describe and predict the behaviour of the heat exchange and the quality of the products produced. A bi-dimensional cold flow model and a CFD model were used to estimate the flow pattern inside the oven by varying the velocity of the air flow in order to simulate changes in the combustion chamber.

Experimental measurements to support improvements in the design and performance of the oven were performed on in situ wood-fired bakery ovens in Mozambique in order to evaluate the dependence of the quality of bread produced on different process conditions that originated from design of oven, the temperature profile and the wood used in combustion. 3D CFD model was also used to study the heat transfer process during the baking process to predict the causes of the differences in quality of the bread baked in same batch. The effects of the design of the oven were analysed concerning velocity, temperature distribution and heat transfer during the baking process.

As much as 60 tonnes/day of green wood are consumed in the bread baking process in the areas investigated. Two types of bakery ovens are used most commonly: indirect and semi-direct. The specific consumption was found to be 0.55 and 0.90 kg of wood per kg of wheat flour baked for the indirect and semi-direct, respectively. The inlet velocity, the geometry and the mode of the feeding dough into the oven affect the flow pattern in the baking oven. The temperature becomes non-uniform, the velocity varies according to the inlet velocity and consequently the quality of the bread baked in WFBO is not uniform.

The analyses of heat transfer from in situ bakery oven shows the dependence on distribution of heat and intensity inside the baking chamber due to the temperature being non-uniform, even with steady temperature conditions in the oven. The heat intensity is affected by burning different wood species. The differences in layers of sand under the oven base give rise to variations of the condition during the baking process.

A mathematical model of the transient heat transfer in a wood-fired bakery oven shows a high accuracy with earlier experimental results. Furthermore, it describes the differences in the distribution of heat in the oven. Fifty per cent of hot gases cross the oven without releasing any heat. The variations in the heat distribution are the cause of the differences in the quality of the bread baked in this device. An example of optimisation using CFD model shows good approximation of the optimal geometry of the oven with reasonable heat distribution. However, the number of the samples must be increased to get the realistic heat distribution, which also requires substantial computing resources.

List of Publications

This thesis is based on the following papers:

I. Manhiça, F. A., Lucas, C. and Richards, T. (2012a) Wood Consumption and Analysis of the Bread Baking Process in Wood-Fired Bakery Oven, Applied Thermal Engineering, 47, pp. 63-72.

II. Manhica, F.A., Lucas, C. & Richards, T. (2012b) Computational Fluid Dynamics Simulation of the Flow Field in Wood-Fired Bakery Ovens. International Journal of Applied Science and Technology, Vol.2 No 7: pp.1-11.

III. Manhiça, F. A., Lucas, C. and Richards, T. (2013) Evaluation of the performance of a wood-fired bakery oven using in situ measurements, JP Journal of Heat and Mass Transfer, Vol.8; No. 2; pp. 119-135.

IV. Manhiça, F. A., Andersson, B., Lucas, C. and Richards, T. (2014) Investigating heat transfer during the baking process in a wood-fired bakery oven using 3D computational fluid dynamics.

   Submitted to Applied Energy.

V. Manhiça, F. A., Lucas, C. and Richards, T. (2014) Improving the Design of Wood-Fired Bakery Oven Using 3D Computer Fluid Dynamics. (Manuscript)

Statement of Contribution

The author of this thesis is the main author of all the papers with guidance from Tobias Richards and support from Carlos Lucas:

Paper I – Performed the field experiments in collaboration with Jose Cirilo and performed the data analyses, writing of the manuscript. The laboratory analyses were performed in collaboration with the technical staff of the Department of Chemical Engineering at Eduardo Mondlane University.

Paper II, III and V – Performed the experiments in cold model at Eduardo Mondlane University and developed the 2D and 3D CFD model, data analyses, writing of manuscript.

Paper IV - Developed the 3D CFD model in collaboration with Andersson, B. data analyses, writing of manuscript.

Conference Contributions (Paper and Poster)

Manhiça, F. A., Lucas, C. and Richards, T., *Technology impact of wood usage in bakery ovens*, 17th European Biomass Conference & Exhibition, From Research to Industry and Markets, CCH - Congress Centre Hamburg, Germany, 29th June – 3rd July 2009

Poster: Proceedings Vol. 17 pp - 1396 - 1399 post

Manhiça, F. A., Lucas, C. and Richards, T., *Two-dimensional description of a wood-fired bakery oven - Physical and mathematical modelling*, SPEIC10 - Towards Sustainable Combustion - Tenerife, Spain 16th-18th June 2010 Oral presentation

Manhiça, F. A., Lucas, C. and Richards, T., *Evaluation of the performance of a wood-fired bakery oven using in situ measurements*, 8th Regional Collaboration Conference and Annual General Meeting – Bagamoyo, Tanzania 1st - 3rd August 2013.

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Special thank you to my team's work in ***Biomass Project*** at the Department of Chemical Engineering at Eduardo Mondlane University in Mozambique.

Dedication

This study is dedicated to my wife, ***Ricardina (Amor Mio),*** and my son, ***Allen,*** for the patience and understanding they have shown for my long and consecutive absences from home. ***I Will Always Really Do Love You!***

*Special dedication I address for my new born twins**, Junior and Yola***, welcome to the world, *you are my sunshine and I wish all the best for them!*

Contents

INTRODUCTION AND OBJECTIVES

1. INTRODUCTION

Strategies for the sustainable development of renewable forms of energy (wind, solar, wave and biomass) in the world typically involve three major technological aspects: making energy savings on the demand side, improving efficiency in the conversion of energy and replacing fossil fuels by various sources of renewable energy. Consequently, plans for implementing the use of renewable energy on a large-scale must include strategies for integrating renewable sources in energy systems that are influenced by energy savings and efficiency measures.

The use of biomass can play an important role since it can be an important source of energy. Deforestation, predominantly in Africa and South America, is very high and is estimated to occur at a rate of about 13 million hectares per year worldwide. Forest plantations and natural expansion have, nevertheless, reduced the net loss of forest area significantly (Cuvilas, 2009). According to "Global Forest Resource Assessment 2005", the amount of land covered by forest has been reduced in Mozambique; it has been estimated that, on average, 3.7% of productive forest (the equivalent of 740,000 ha) was lost during the last 15 years. This deforestation was motivated by the need to exploit timber, creation of new agricultural and residential areas, production of coal, and to provide wood for domestic usage. It is estimated that 17 million m^3 per year is extracted from the forest for cooking purposes alone (Sal and Caldeira, 2008).

Mozambique is a country with considerable forest resources; the main source of energy for different activities is based on biomass, as shown in Figure 1.1. These resources are of particular importance to the country, given its social, economic and environmental impact. Perreira *et al.* (2001) estimated that about 70% of the population depends on energy derived from the forest. A recent estimation by GRNB (2008) showed that the demand for wood fuel has continually increased over the last two decades. At present, 80% of the energy used comes from biomass, which represents an annual average consumption of wood fuel per capita in urban areas, estimated at 1.2 m^3 and 1.0 m^3 in rural areas (GRNB, 2008). A study by Vasco *et al*. (2009) concluded that forest fires afflicted about 58,393 ha in Mozambique: 561 ha were in the province of Maputo, and mainly in the districts of Magude, Moamba and Manhiça. The total growth of forest biomass, in Maputo province alone, is estimated to be 1,233,000 tonne/year, with the corresponding amount of available energy being 17,268,000 GJ/year (Vasco *et al*. 2009), assuming an average heating value for the biomass of 20 MJ/kg (Duke, 1983) using 70% energy efficiency. Table 1 shows the biomass energy potential of the districts in the province of Maputo.

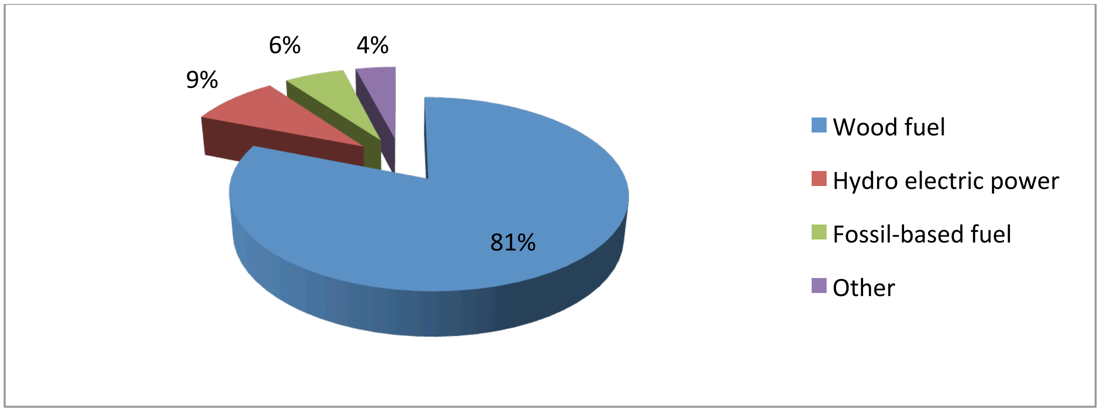


Figure 1.1: Balance of energy demanded in Mozambique in 2006 (ME, 2006)

Table1 – The energy potential of each district in the province of Maputo (data from Vasco *et al.*, 2009)

District	*Available biomass (tonnes/year)*	*Estimated energy potential (GJ/year)*
Boane	18,444	258,209
Maputo city	8971	125,599
Magude	450,416	6,305,825
Manhiça	135,048	1,890,667
Marracuene	20,139	281,942
Matutuine	325,126	4,551,767
Matola	4110	57,546
Moamba	225,936	3,163,099
Namaacha	45,223	633.116
Total	***1,233,412***	***17,267,771***

1.2. The Use of Biomass

Energy based on wood is used by households, industries, commercial enterprises and institutions mostly in rural zones, but also in urban areas such as Maputo city. Although wood fuels are gathered mostly by individuals for personal use, wood and charcoal have become trade goods in many places, particularly so in urban areas. Both urban and rural households at almost every income level buy wood fuels. The industries and enterprises also buy wood to meet their energy requirements. An estimation of the wood demand for Maputo city and Matola indicates a consumption of forest biomass residues by the population of about 650,000 tonne/year (Vasco *et al.* 2009).

Industries using wood fuel contribute significantly to the generation of income and socio-economic development in rural and urban zones. In recent years, wood fuels have been used increasingly for industrial applications, mainly in the bread baking process. However, the technology and the energy conversion devices employed are generally poor as well as inefficient, so the scope for improving them both is large.

1.1. The Wood-Fired Bakery Oven (WFBO) and the Bread Baking Process

Wood-fired bakery ovens are the type commonly used in Mozambique. The oven, which is heated by combusting biomass, is made of a refractory ceramic material. The combustion chamber is a parallelepiped with a circular top, the end of which is funnel-shaped to lead the duct that joins the chambers out via the furnace grid. A typical baking chamber has an arched roof with a circular or elliptical base and is connected to a chimney at the top that allows the gases to exit. These kinds of bakery ovens are constructed by the colonial government to produce bread for minor groups of residents as a result of the general scarcity of electrical power in Mozambique. The large-scale bakeries are, on average, more than 35 years old.

New technology is available that utilises the forced combustion of biomass. The high cost of electricity and maintenance, however, mean that this is not cost-effective for the majority of enterprises interested in, or even considering, increasing the efficiency of traditional wood-fired bakery ovens.

The main characteristic of wood-fired bakery ovens (also known as semi-direct bakery ovens) is the two chambers: the combustion chamber and the baking chamber (baking oven). The former is where the combustion of wood occurs. Heat is then transferred via the combustion gases to the latter, i.e. the baking oven. Figure 1.3.1 shows the technical design of such a bakery oven.

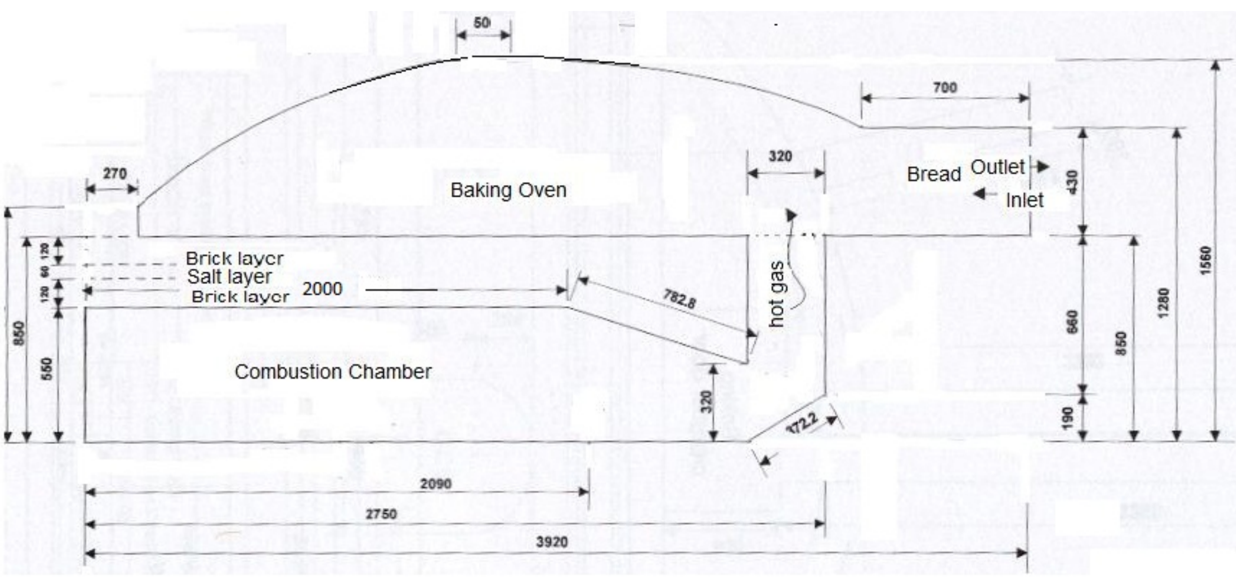


Figure 1.3.1: A longitudinal cross-section of a semi-direct bakery oven (a type of wood-fired bakery oven).

Most of the bread consumed in Mozambique is produced by the following sequence of events: weighing the ingredients, mixing, fermenting, scaling, rounding, bench proving, moulding, panning and pan proving, baking and, finally, cooling. The bread used in this study, was leavened, and made according to the following recipe for one batch: 50 kg wheat flour, 0.750 kg coarse white salt, 0.5 kg composed yeast, 0.125 kg improver (VITA M7 1%) and 33–36 litres of water. The baking method used is as follows:

1. The raw materials (wheat flour, water, salt and ferment, i.e. yeast) are mixed together to create a high degree of homogeneity. This incorporates the fermented cells and ferments the dough: this reduces the fermentation time considerably and increases the quality of the bread with respect to softness and size.

2. The dough is weighed, divided and moulded before being allowed to rest (i.e. prove) in order to rise to an optimal size in preparation for baking.

3. The dough is then placed into the furnace for baking at temperatures of 200–250ºC. The baking time, which depends on the size of the loaves and the kind of oven used, is usually between 15 and 30 min. When removed from the oven, a loaf crust has moisture content of 1–2% and an inner temperature of around 99ºC. The moisture content of the crust increases rapidly once the bread is removed from the oven due to moisture transport from the crumb.

4. The loaves are cooled. At the beginning of the cooling process, heat and mass are transferred by an evaporation-condensation mechanism inside the crumb and the high vapour pressure gradient that exists between the centre of the crumb and the surface crust. The mass transfer increases the apparent thermal conductivity of the crumb. The cooling rate also depends on the temperature and relative humidity of the air. According to Mahassa (1995), Lucas (1995) and Tsamba (1994), increasing the cooling rate by decreasing the temperature of the air may cause the intense mass transfer to move towards the crust surface by slowing down the rate of evaporation. This may, however, cause condensation to form below the crust layer and create a higher degree of water activity. This, in turn, would have the negative impact of encouraging microbial growth during storage.

1.3. Characteristics of Wood and the Efficiency of Wood-Fired Devices

The most important properties of wood used as fuel are its heating value, moisture content, density, size and content of ash; physical characteristics, chemical composition and the conversion method used define its quality. An important factor affecting the way in which firewood burns is its condition. Hardwood is preferred in most cases, as it tends to produce a longer-lasting burn: Acaceas Sp (Red and White Micaia), Unknown (Nkonola and Xihoho) wood are preferred by most bakeries (Tsamba, 1994; Cuvilas, 2009).

Typical problems associated with a wood-fired bakery oven can easily be described through observation of the chimney outlet. If the plume of smoke rising from the top of the chimney is blue or grey instead of clear or white, it is an indication of smouldering, poor combustion, air pollution and (probably) operating temperatures that are too low. The normal action of the oven operator is to position the combustion chamber door in such a way as to increase the intake of air so the smouldering fire soon turns into a flame. Rearranging the position of the firewood is another method of improving combustion in the combustion chamber. Pieces of wood laying loosely in a criss-cross pattern burn quickly, regardless of their size, as the combustion air can easily reach all of the pieces (i.e. there is a large active surface). The larger pieces in a compact pile burn more slowly than the smaller pieces because there are fewer spaces for the air to penetrate the load.

The wood fires burn in cycles. A cycle starts when a new load of wood is ignited by a charcoal bed and ends when that load is consumed and, thereby becomes the bed for the next fire. Each cycle provides three to eight hours of heating depending on the amount of wood loaded, the amount of heat that is needed and the size of the combustion chamber. The efficiency and convenience of a wood-heated system depend greatly on the quality of the fuel wood burned. The four main factors that influence the way in which firewood burns are: the tree species, along with the moisture content, size of the individual pieces and the condition of the wood.

The geometrical design of a bakery oven is not standardised, but instead reflects local conditions. Differences in the configuration and size of baking ovens result in every wood-fired oven behaving differently, with each having its own heating time (i.e. baking time). It is therefore not possible to give the exact temperatures prevalent inside a typical baking oven. However, as a guideline, the bakery oven operator never allows the bread surface (crust) to become dark brown in colour.

1.4. Aims and Objectives

The main objective of this research is to improve the aerodynamics and heat transfer in existing wood-fired ovens in order to increase the efficiency of the oven and to increase the quality of the bread, as well as to design a prototype, wood-fired, small-scale furnace (i.e. bakery oven).

To achieve this objective, measurements were performed in a variety of ovens, including *in situ* WFBO to be used as references to build up theoretical models. A bi-dimensional cold model and mathematical models will be used, based on parameters such as the aerodynamics, mixing, residence time and recirculation of the gases; kinetic, physical and chemical processes of wood combustion; and the environmental impact of the combustion of different species of wood on the technology actually applied in the baking process to improve the geometry of oven.

BACKGROUND

2. BAKGROUND

The baking process is a key step when making bread; it is where a lump of dough is transformed into a light, porous, readily digestible and tasty product under the influence of heat. The production of bread presumes a carefully controlled baking process in order to meet these requisite quality attributes. Factors influencing the final quality of the product include: the rate and amount of heat applied, the humidity level in the baking chamber and the baking time. The most important stages during the baking are: volume expansion, crust formation, inactivation of yeast and enzymatic activities, and protein coagulation and partial gelatinisation of starch in the dough and moisture levels. It is highly desirable that optimal temperature profiles and baking times are established in order to produce bread with low levels of moisture loss at consistent and acceptable levels of quality (Therdthai *et al*., 2002).

2.1. Dough and Bread

Bread requires flour, mostly wheat flour, and water to form gluten. Gluten network hinders the gas produced by the added yeast from leaving the dough during the baking process. The gas formation causes an expansion in volume, thereby increasing the bread porosity. Water is not only important for the formation of gluten, but also for changing the properties of the bread such as texture, colour and taste.

Dough

The dough, which is mainly composed of starch and gluten, consists of a continuous phase and a dispersed gas phase with a foam structure. The structure of the bread crumb has both fibrous and sheet-like gluten layers. After appropriate mixing of the raw materials, the fermentation process starts in which the yeast forms carbon dioxide gas continuously. As the temperature increases, the starch granules absorb water, gelatinise and swell thereby removing water from the gluten. Consequently, the chemical composition change from dough to a crumb; just before the dough becomes semi-rigid bread, the pore structure opens up (Thorvaldsson *et al*., 1998).

Bread

Bread is composed of crust and crumb, the proportions of which depend on the conditions in the oven. Crumb has a porous structure; it consists of a monomolecular lipid with a few, polymerised, protein units of high molecular weight dispersed within it. The walls of the pores are composed of dried gelatinised starch. According to Therdthai *et al.* (2004), the curvature of pores has three functional aspects that affect:

1. The structure of the bread.
2. The mechanism of heat transfer, particularly the evaporation and condensation of water vapour through/within the pore system.
3. The adsorption of the flavour compounds formed during baking.

The crust is a hard, vitreous layer formed of dried and collapsed pore walls of crumb; crust is formed when the temperature increases and more water evaporates from the surface, which, in turn, activates non-enzymatic browning reactions. The thickness of the crust follows the 100ºC isotherm inside the product (Therdthai and Zhou, 2003).

A typical baking process can be divided into three stages: in the first, the temperature of the outer crumb increases at an average rate of 4.7ºC per min up to 60ºC. This increase enhances enzymatic activity and growth of yeast, resulting in an increase in volume of the crumb inside the oven, an expansion in the order of one-third of the original volume. Furthermore, the surface loses elasticity, thickens and starts to take on a brown appearance. According to Swortfiguer (1968) and Therdthai *et al*. (2002), this stage takes one-quarter of the total baking time. In the second stage, the temperature of the crumb increases at a rate of 5.4ºC per min to 98.4–98.9ºC before it remains constant. At this temperature, all reactions are maximised, including the evaporation of moisture, gelatinisation of starch and the coagulation of protein. The dough turns into crumb from the outside in, i.e. towards the inner parts, when heat is transferred inwards. A typical browning crust can be observed when the temperature at the crust reaches 150–205ºC. According to Pyler (1973), this period takes about half of the baking time. The final stage is the volatilisation of organic substances and is designated the "bake-out loss". This stage takes about one-quarter of the total baking time. Wong *et al.* (2006) use the same classification, with the exception that they divide the second stage into two subgroups: the gelatinisation of starch followed by the coagulation and denaturalisation of protein.

2.2. Heat and Mass Transfer Mechanisms during Baking

Heat is transferred during the baking process via a combination of conduction, radiation and convection.

Conduction is the transfer of heat from one part to another of the same body, or from one body to another, where a physical contact exists. The Fourier's Law equation describes the mechanism (Eq 2.1):

$$q = k\frac{dT}{dx} \qquad \textit{Eq 2.1}$$

where q is the heat flux (W/m^2), k is the thermal conductivity (W/mºC), x is the distance (m) and T is the temperature (ºC).

Radiation. The quantity of heat transmitted between two bodies by radiation, is in direct proportion to the difference between the fourth powers of the absolute temperatures between the bodies. Heat transferred via radiation is described by (Eq 2.2)

$$q = \sigma\varepsilon(T_h{}^4 - T_b{}^4) \qquad \textit{Eq 2.2}$$

where q = Q/A is the heat flux (W/m^2), Q is the rate of heat energy transfer (W), A is the surface (m^2), σ is the Steffan-Boltzman constant (5.67x10^{-8} W/m^2.K^{-4}), ε is the emissivity of the body, T_h is the temperature of the heat source (K) and T_b is the temperature of the heat-absorbing body (K).

Convection is the term used to describe the heat transfer that occurs when one part of a volume of gas or liquid is physically mixed with another part. In the case of air, its density decreases as it is heated, causing it to move upwards; cooler air, with a higher density, moves downwards. This natural mechanism of convection can also be found in wood-fired bakery ovens. Assuming that the body has a large thermal conductivity compared to the fluid, and the temperature difference is low in the body compared to that of the fluid, then Eq. 2.3, the first law of thermodynamics, describes the equivalence between the body temperature and internal energy variation per unit time and the heat transfer by convection with the fluid:

$$\rho cVdT / dt = hA(T_f - T) \qquad \textit{Eq. 2.3}$$

where V is the volume and A is the surface of the body. Using the initial condition of the body temperature, T_0 , the temperature change can be expressed as Eq. 2.4:

$$(T - T_f)/(T_0 - T_f) = \exp - (hA/(\rho cV)t) = \exp - \lfloor (hL/k)(\alpha t/L^2) \rfloor \qquad \textit{Eq. 2.4}$$

where L=V/A is a characteristic dimension that depends on the geometry of the body. The group represented by hL/k is called the Biot number (Bi) and represents the relationship between the external and internal transfers of heat. The variable $\alpha t/L^2$ is known as the Fourier number (F_o) and is a measure of the thermal diffusivity.

In case of forced convection (i.e. air is forced to move by measures other than differences density, e.g. by using fans) in the oven, the convection can be described as Eq 2.5.

$$q = h(T_a - T_b) \quad \text{or} \quad Q = hA(T_a - T_b) \qquad \textit{Eq 2.5}$$

where q is the heat flux (W/m^2), h is the heat transfer coefficient (W/m^2.ºC), T_a is the air temperature (ºC), and T_b is the body temperature (ºC).

According to De Vries *et al.* (1989) and Wagner *et al*. (2007), the heat transport inside the dough occurs by four mechanisms. Water evaporates at the warmer side of a gas cell. The water vapour produced then moves through the gas phase and, when it meets the cooler side of the gas cell, condenses and becomes water once again as it releases energy. Finally, heat and water are transported by conduction and diffusion through the gluten gel to the next cell. The principle of the evaporation-condensation model that was developed to explain heat transport during baking could not alone explain the actual heating rates, which are faster. The thermal diffusivity in the foam is lower than that of a continuous phase, due to the presence of insulating elements such as gas bubbles (Gori, 2004).

Zanoni *et al*. (1993) proposed a mechanistic model to describe the heat and mass transfer phenomena that cause a series of physical, chemical and structural transformations in bread. The model is able to determine the temperature, moisture, crust thickness and increase in volume. Initially, convective evaporation of water occurs at the surface of the loaf, where it is exposed to air; the temperature of the crumb increases linearly with time until it reaches 100ºC. Unbound water evaporates at this temperature and boiling occurs. Studying the proposed model, it is assumed that the temperature at the evaporation front is 100ºC during whole process. In the crust, above the evaporation front, all of the bound water was evaporated. As a result, the temperature of the crust increases and approaches that of the oven. The crust becomes thicker when the evaporation-front advances progressively inwards.

Tong and Lund (1993) developed a one-dimensional mathematical model of heat diffusion using the internal generation of heat. The principal model involves the transfer of water in the vapour phase, the content of water in the hygroscopic range and content of moisture at equilibrium at the surface of the product during baking. Similar parameters were used when Zanoni *et al*. (1994) developed a two-dimensional axi-symmetrical heat diffusion model. The phenomena were separated into upper (crust) and lower (crumb) sections. In general, the model combined the temperature of the crust, determined by equations including heat supply via convective mass transfer towards the outside, and the temperature of the crumb, determined using Fourier’s law.

Thorvadsson and Skjoldebrand (1998) concluded that the water contained in the centre of the loaf rises during the baking process. This water moves towards the centre as water vapour is evaporated near the surface, where the temperature is higher, and condenses closer to the centre, where the temperature is lower.

Thorvadsson and Janestad (1999) developed a model with heat, water and vapour diffusion. The model is based on Fourier’s and Fick’s law and divided into two parts: the diffusion of liquid water and the diffusion of water vapour. De Vries *et al.* (1989) also established a one-dimensional, cylindrical, co-ordinate model. Zhang *et al.* (2007) applied combined mechanisms, leading to the expansion of gas cells (CO_2) and the dough/crumb transition, to all typical baking processes. Lucas *et al*. (2007) continued to study the effect of CO_2 and proposed an experimental method to correlate release of CO_2 with baking parameters. They used infrared detection and gas chromatography, and investigated the effects of two process parameters on the release of CO_2 on the proving time and temperature of the oven. The concentration of CO_2 measured by infrared detection, which showed little difference to the gas chromatography method, was judged to be the more convenient of the two; it also provided more stable measurements.

Jefferson *et al*. (2007) discussed the model and the numerical method based on changes in the dough during baking. The dough can be considered as being a bubbly liquid when it is placed in an oven. The model assumes that the setting and fracturing occur at the precise temperature when fracturing reaches a bubble; the part of the bubble adjacent to the liquid dough collapses instantaneously. This collapsing mechanism, with a change in density fixed by the temperature gradient, is coupled to a non-linear heat equation, with an experimentally defined thermal conductivity and an evaporation boundary at 100ºC. It also allows for convection due to the expansion of the inner (unset) part of the dough. The method identifies how qualities of the crust, namely its size, thickness and mass, depend on various physical properties (such as the water content of the dough) and might be determined by the quantity of the flour used.

2.3. Heat Transfer within an Oven Chamber

In an oven chamber, molecules of air, water and/or combustion gases circulate throughout, transferring heat by convection. Radiant heat, which originates mainly from the burner flames and all hot metal parts in the oven, has two characteristics that are different from other heat transfer mechanisms, which are important in bakery ovens. First, it is hindered by shadowing or blocking by intervening layers that are opaque and, secondly, it is responsive to changes in the absorptive capacity of the responding media, i.e. the dough (Therdthai *et al*., 2003).

Carvalho and Martins (1991) developed a three-dimensional mathematical model for heat and mass diffusion, using the “finite difference” method, to study the evaporation and condensation of water in the product. They also considered the conservation equation for mass, momentum, enthalpy, moisture and the turbulence model (k-ε) together with the radiation heat transfer of the turbulent flow in the baking chamber. The variables used in the model were effective physical properties such as thermal conductivity, specific heat, density (as a function of temperature) and volume expansion.

Carvalho and Nogueira (1997) showed that, for bread, the velocity of the airflow in an oven chamber influences the heat flux and the bread properties, as well as gives possibilities of optimising the distribution of the flux. Radiation was also confirmed as being the most important mode of heat transfer in the baking process for the highest layer of loaves in the ovens, and particularly so for natural convection ovens. This coincides with the results of a CFD model developed by Velthusis *et al*. (1993).

CFD modelling has been used to deal with the complex heat distribution, product geometry and configuration of ovens. In order to prevent the leakage of gas in a heating duct leading to an oven chamber, Fuhrman *et al*. (1984) used CFD to simulate the fluid mechanical and thermo dynamical state within the oven to ensure that the system could maintain the pressure in the heating ducts lower than the ambient pressure. Carvalho and Martins (1991) also used the CFD modelling technique to investigate the proportion of the heat transfer mode that included radiation and convection within natural convection and forced convection ovens. The CFD approach was applied to study the effect of a perforated plate on improving the homogeneity of an assumed velocity field and the pressure drop across the baking chamber in a laboratory batch oven (De Vries *et al*., 1995). Verboven *et al*. (2003) used CFD simulation to find a way of increasing the mass transfer coefficient and the uniformity of heat coefficient at the surface of the product.

Gupta (2001) developed a model for estimating the fraction of heat transfer modes applicable when making Indian flat bread (i.e. chapatti) in a continuous baking oven; it was found that conduction was the most important mode of transferring heat from the oven chamber to the product. This is not in contradiction with previous studies, due to the geometrical characteristics of a chapatti; it is thin (1.0–1.5 cm in thickness) and has a short baking time (about 40 s). However, the model neither considered the direction of the heat and its flow to the product nor the dynamic change of the oven load during continuous baking.

2.4. Mass Transfer during Baking

Tong and Lund (1993), Zanoni *et al*. (1993), Zanoni *et al*. (1994) and Thorvaldsson and Janestad (1999) assumed that the mechanisms of mass transfer within the dough could be described using the mechanisms of evaporation and condensation. The experimental results of Thorvaldsson and Janestad (1999) showed that the concentration of water measured, at the centre of the bread, decreased until the temperature at the centre reached 70±5ºC due to the expansion in volume. The total water content of the bread is constant because the dough does not have a continuous pore system, which obstructs the transport of water severely. When the temperature reaches 70ºC, structural changes begin to take place and, as a result, the discrete pores become connected, allowing water to thus move more freely.

In an attempt to reduce the pressure of the water vapour due to the temperature gradient, water moves towards the centre of the loaf of bread as well as to its surface by means of evaporation and condensation. As a result, the increase in temperature at the crumb accelerates. At the surface, the surrounding gases are not saturated; the evaporated vapour is transported through the diffusion layer and exits the loaf. The movement of moisture in the crumb and crust can be described by Fick's law, as shown, for example, by Sablani *et al*. (1998) and Thorvaldsson and Janestad (1999).

Sablani *et al*., (1998) describe a general equation for the distribution of both temperature and moisture within bakery products that defines the boundary conditions in a form different to that of Therdthai and Zhou (2003). Their model for the combined transfer of heat and mass in dough during the baking process can be presented as follows:

$$\rho_b c_{P_b} \frac{\partial T}{\partial t} = \nabla(k_p \nabla T) + \rho_b \lambda_v \frac{\partial C_s}{\partial t} \qquad \textit{Eq 2.6}$$

$$\frac{\partial C}{\partial t} = \nabla(D \nabla C) \qquad \textit{Eq 2.7}$$

with the boundary conditions:

$$k_p \nabla T \cdot \vec{n} = h_t(T_a - T_s) + \varepsilon\sigma(T_w^4 - T_s^4) \qquad \textit{Eq 2.8}$$

$$D \nabla C \cdot \vec{n} = h_m(C_a - C_s) \qquad \textit{Eq 2.9}$$

$$\frac{dC_s}{dT} = k(C_g - C_s K(T)) \qquad \textit{Eq 2.10}$$

where ρ_b is the apparent density, c_{pb} is the bulk specific heat, T is the temperature, t is the time, k_p is the thermal conductivity, λ_v is the latent heat, D is the water diffusivity, h_t is the convective heat transfer coefficient, h_m is convective mass transfer coefficient, k is the rate constant for the phase transport from gas to liquid, C is the absolute moisture content, ε is the emissivity and σ is the Stefan-Boltzmann constant. The following subscripts apply: *a* for air, *s* for surface, *g* gas phase, and *w* for walls. *K(T)* is the equilibrium constant of the evaporation which can be expressed by Eq.2.11.

$$K(T) = Ae^{\frac{-\lambda_v}{RT}} \qquad \textit{Eq 2.11}$$

where *A* is called the pre-exponential constant.

Thorvaldsson and Janestad (1999) divided the moisture content, C, further into liquid water and water vapour, which diffused separately and simultaneously within the dough. Saturation equilibrium was assumed to be reached between the liquid water and the water vapour.

2.5. Physical Changes during Baking

Structural Changes

According to Chevallier *et al*. (2002), the macroscopic modifications that occur during the baking process can be divided into three stages: (i) the development of a partially open and porous structure associated with the decrease in density, (ii) drying and (iii) colouring of the surface. Structural changes are the result of water vaporisation and the gas bubbles that are produced when the chemical leavening agents decompose. The bread stops expanding in size when the chemical leavening agents becomes depleted and there is no more percolation of water vapour at the appropriate temperature.
Therdthai *et al*. (2003) considered two major structural phenomena during the baking process: the first is the transformation of semi-fluid dough into a predominantly solid, baked product that is characterised by certain rheological properties. Changes in the rheological properties are, naturally, affected by the baking conditions. The second is the expansion of the dough in the oven until the structure becomes fixed. The main physical change occurring during the baking process is the loss of moisture, since it is related to the transfer of both heat and mass. Almost all moisture lost during the baking process is due to evaporation; variations in such losses are caused by the nature of the dough and the baking conditions. According to a model based on water evaporation and diffusion (Therdthai and Zhou, 2003), it was found that the water content in the crumb after baking was the same as the initial water content of the dough. Almost no water was predicted to be present in the crust, so the total loss of moisture occurred basically from the surface. Based on a total moisture loss of 53 g per loaf, Thorvaldsson and Skjoldebrand (1998) found that 29 g was lost from the top crust, 12 g from the layer below the top crust and 12 g from the side crust. Figure 2.5.1 illustrates typical changes in the content of water in the top crust, centre and base of the loaf, respectively, during the baking process, (Thorvaldsson and Skjoldebrand, 1998).

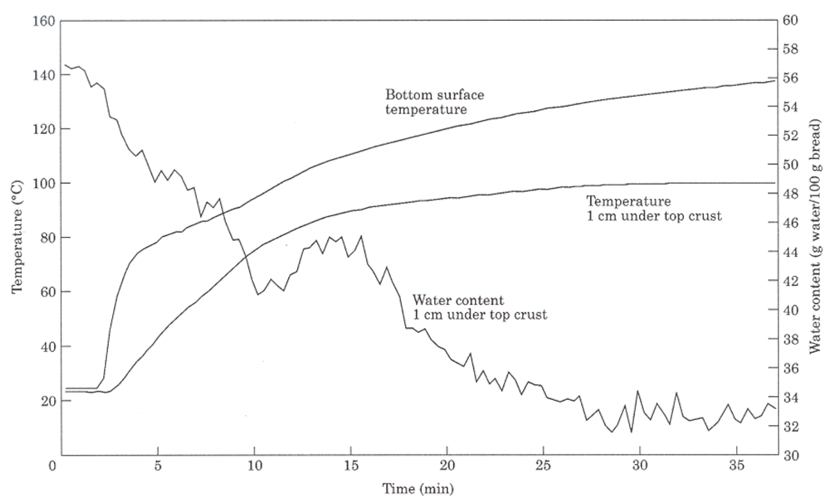


Figure 2.5.1: a) Water content and temperature profile in the top crust (from Thorvaldsson and Skjoldebrand 1998)

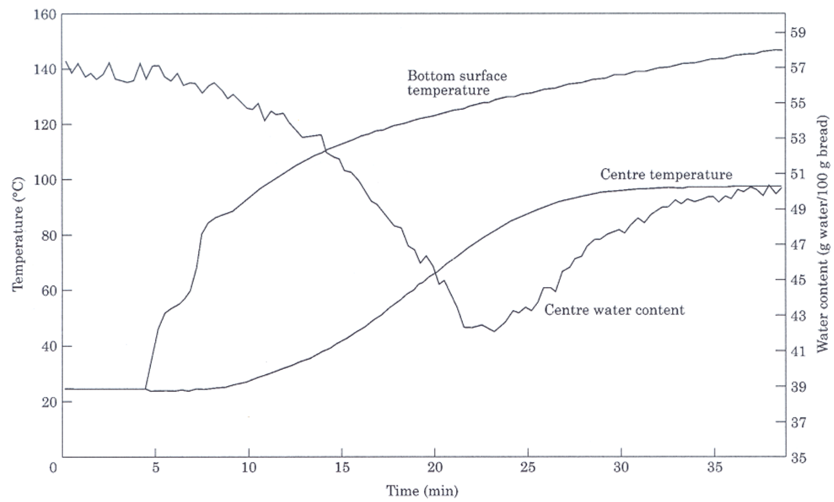


Figure 2.5.1: b) Water content and temperature profile in the centre (from Thorvaldsson and Skjoldebrand 1998)

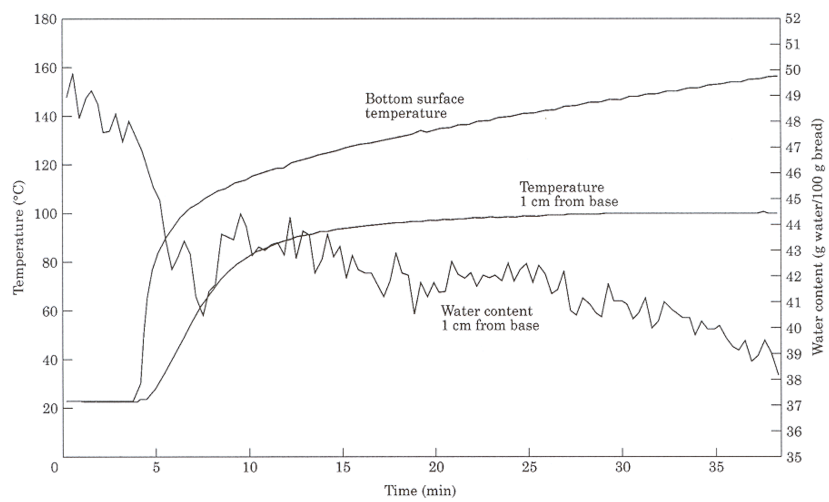


Figure 2.5.1: c) Water content and temperature profile in the bottom surface (from Thorvaldsson and Skjoldebrand 1998).

2.6. Effects of Baking Parameters on the Quality of the Product

The quality of the loaves produced depends largely on the heat treatment received by the pieces of dough during the whole of their residence time in the oven. The common industrial practice employed to achieve optimal results is to bake the bread at a constant temperature. Uneven distribution of temperature and random disturbances in the oven often result in the dough being subjected to inconsistent heat treatment (Wong *et al*., 2007). Hadiyanto *et al.* (2007) presented a systematic approach that captures the most dominant physical phenomena and the transformation in the product during baking; they developed a model based on interconnections between input, heat and mass transfer, product transformation and attributes of product quality which represents the total behaviour of the product. The simulation describes how product attributes can be modified by changing the initial composition and process variables during baking, and allows the various processing alternatives to be ranked.

Temperature

The baking temperature dominates the quality of the product during baking. The increased temperature creates a pressure gradient in the product; causing the lattice of the gluten threads to dilate from the centre of the loaf outwards, i.e. towards the surface, see Figure 2.5.1. Figure 2.5.1:b) shows a typical graph of the changes in temperature and water content in the centre of a loaf during baking. Near the base, 1 cm into the loaf, the water content first decreases as drying occurs (this corresponds to a water loss of about 9 g water / 100 g bread). When the temperature has reached 70 ± 5°C, there is an increase of water content due to increased temperature in the whole loaf which leads to that water being transported from the inside and out. This increase is rapid and equals approximately 2 g water/100 g bread. Thereafter, it slowly decreases and the total loss of water during this period is 4 g water/100 g bread (Figure 2.5.1: c). At 1 cm underneath the top surface, the changes in the measured water content are similar, although the initial rise is approximately 3 g water/100 g bread and the decrease is approximately 13 g water/100 g bread (Figure 2.5.1: a). At the top and absolute bottom, the decrease in water content commences immediately and a crust is formed.

Not only is it important to know what temperature is necessary to bake the bread but also when it should be applied; the optimum temperature must be reached at the right time, otherwise, the quality of the product may be degraded.

Patel *et al*. (2005) compared the characteristic of products produced at different heating profiles during baking. Moisture and water activity, firmness, thermal properties of starch and other properties were found to be dependent on the heating rate during the baking process. The development of browning during baking is a dynamic process mainly influenced by temperature and water activity of the system (Purlis, 2010). Browning occurs from the accumulation of coloured compounds produced by the Maillard reaction and by caramelisation. It affects the overall quantity of food and is partly responsible for changes in sensorial attributes such as colour, flavour and aroma. The development of browning depends on the dough formulation (i.e. amino compounds, sugars and leavening agents) and the operating conditions (i.e. temperature and water activity) (Purlis, 2010). Variations in temperature affect water activity (aw) directly which, in turn, determines the level of microbial activity. The water content and its distribution determine textural properties such as softness of the crumb, crispness of the crust and shelf life (Wagner *et al.,* 2007). Thorvaldsson and Skjoldebrand (1998) showed that the temperature profile during the baking process influences the quality of the bread produced.

Thorvaldsson and Skjoldebrand (1998) used the surface temperatures of the product instead of the temperature of the air to study the quality of the outermost layer of the loaf. It was noticed that the temperature at the bottom surface increased slightly faster than at the side surface. An alternative way of measuring the combined influence of the baking temperature and other parameters is to measure the heat flux. Therdthai *et al.* (2002) and Wong *et al*. (2006) developed a CFD model that was used to combine the temperatures measured by the top, side and bottom heat sensors to obtain an average, weighted, temperature for each of the zones in the oven to predict the quality of the product. The heat flux is defined as the rate of heat transfer per unit area required by the product. It is claimed that it is more useful to measure the heat flux than the gas temperatures when controlling the quality of bakery products, (Fahloul *et al*., 1995; Carvalho e Nogueira, 1997). Figure 2.6.1 shows a typical temperature profile during the baking process in a forced convectional oven at 225ºC (Thorvaldsson and Skjoldebrand 1998).

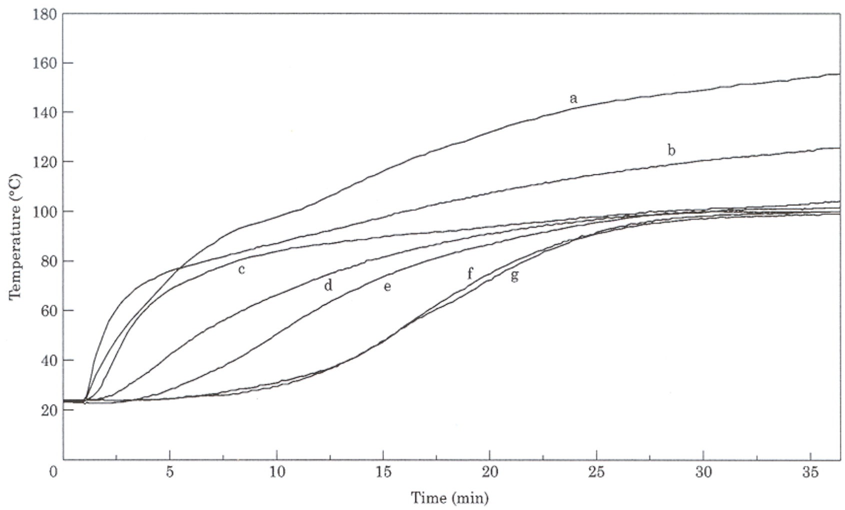


Figure 2.6.1:
a) Top surface, b) Bottom surface, c) Side surface, d) 1 cm from the bottom surface, e) 6.8 cm from the bottom surface; f) Centre, 4.6 cm from the bottom surface, g) 3.5 cm from the bottom surface. Total height 9.0 cm (from Thorvaldsson and Skjoldebrand 1998).

Airflow Velocity

The CFD models clearly show that increasing the velocity of the airflow in the oven chamber increases the heat flux to the product; a change in the composition of the gas in the chamber during baking also affects the heat flux (Carvalho and Mertins, 1991; Velthuis *et al*., 1993; De Vries *et al*., 1989; Mirade *et al*., 2004). When the oven chamber was filled with radiation absorbing gases (i.e. water vapour and carbon dioxide), the average temperature was estimated to have increased by 5ºC (Velthuis *et al*., 1993).

The velocity of the gas flow also affects the quality of the baking process. Lack of uniformity in the end product is possibly due to the non-uniformity of the flow of gas around the product during baking. Temperature on the bread surface was increased by increasing the velocity of the gas flow (Velthuis *et al*., 1993; Carvalho and Nogueira, 1997). Experience from the baking process showed that an increase in the velocity of the gas flow results in greater weight loss, less softness and darker surface. It is, therefore, concluded that either the baking time or the baking temperature should be reduced with respect to increasing the transfer rate of heat. The baking process does, however, require a minimum temperature to produce an adequate colour. When bread is baked at a very low temperature, a very high velocity of the gas flow is required in order to increase the drying rate and produce an acceptable crust colour.

Therdthai and Zhou (2003) simulated, in two-dimensions, the temperature profile and gas flow pattern throughout the baking chamber of an industrial, continuous, baking oven (16.5 m long, 3.65 m wide and 3.75 m high). The CFD results provided enough information to establish the optimum baking temperature profile and where to position the control sensors. Verboven *et al*. (2003) increased the gas flow velocity to overcome the problem but, as a result, the heat and mass transfer coefficient were not increased enough to remove the accumulation of moisture effectively. When the mass transfer coefficient was sufficiently high to reduce the water content on the surface significantly, the colour and development of flavour could be enhanced at the same time as the texture improved. Mirade *et al*. (2004) used a two-dimensional CFD model to predict the velocity of the gas and the temperature fields necessary in the baking chamber of an industrial, gas-fired, tunnel oven used for baking biscuits. Whilst comparing calculations with measurements revealed a fairly close agreement in the temperature profile of the gas in the baking chamber of the tunnel oven, a fairly large discrepancy was found in the velocity profiles of the gas.

Baking time

The kinetic reactions, including the gelatinisation of starch and the browning reaction, depend not only on temperature but also on baking time. It must be ensured that the gelatinisation and browning reactions have been completed if the baking time is to be reduced by either increasing the airflow velocity or the baking temperature; otherwise, the quality of the product may be degraded (Therdthai *et al*., 2002). Even if the gelatinisation and browning reactions are complete, the quality of a product baked for a short time can differ significantly from one baked for a longer period. Longer baking times can, in fact, result in caving as well as reduced softness. It is necessary for the baking temperature and baking time to be synchronised for optimal production of the product desired (Therdthai *et al*., 2002).

Humidity

An increase in the humidity of the gas, created either by injecting water vapour into the oven or the migration of water vapour from the product, increases the flow of heat. According to a CFD model, the average temperature of an oven composed of pure water vapour can be 5ºC higher than that of an oven containing only dry air (Velthuis *et al*., 1993) due to water vapour having a greater ability to absorb radiated heat. Water vapour, on the other hand, may limit the formation of crust (Chevallier *et al*., 2002) and is therefore normally only applied to an oven at the beginning of a baking process for bread products. Insufficient control of water vapour could, however, render too low a level of humidity in the oven chamber, with the result that the baking loss may increase (Therdthai and Zhou, 2003).

2.7. Specific Characteristics and Design of Baking Ovens

The manner in which heat is supplied and then transmitted to the baking product, the control of the amount and intensity of heat required for the baking process and the cost of construction, operation and maintenance of the baking unit are all important parameters pertaining to the design and development of modern baking ovens. An oven is basically composed of a baking chamber and a heating system. The baking chamber is normally designed as a rectangular box comprised of a steel-lined sheet supported by a steel frame. The oven walls are insulated on the top, bottom and sides. According to Pyler (1973), the ovens can be divided into four types: reel, tray, tunnel and spiral.

A *reel oven* consists of a relatively high baking chamber that houses a vertically-revolving reel on which the baking trays are suspended in a ferris-wheel fashion between the two side members of the reel, see Figure 2.7.1. This oven can be either fired directly, when electricity or gas is employed, or indirectly, when oil is the fuel used.

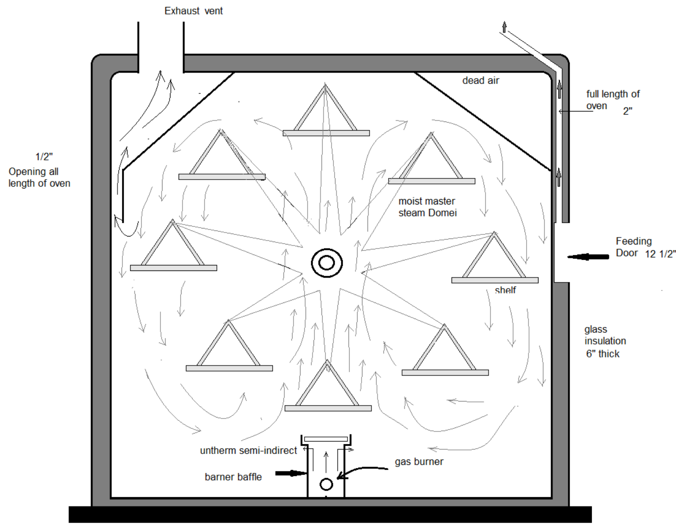


Figure 2.7.1: Cross-section of a reel oven (redrawn from Pyler 1973)

A *travelling tray oven*, of either single or double lap design, is essentially a modification of the reel oven; it differs in that it has a much lower horizontal baking chamber in which the rotating reel is replaced by endless chains that support the baking trays, see Figure 2.7.2. In a single lap tray oven, the baking trays move back and forth once during the baking process whereas in a double lap tray oven, they travel back and forth twice.

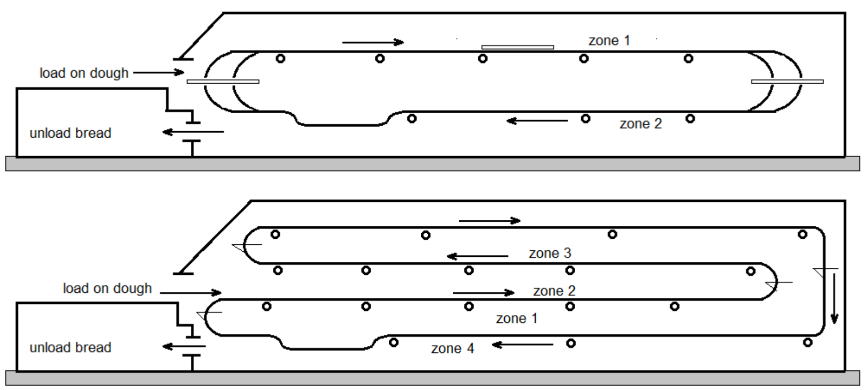


Figure 2.7.2: Schematic diagram of a single lap and a double lap oven (redrawn from Pyler 1973)

A *tunnel oven,* or travelling hearth oven, is designed primarily for large volume, continuous operation. Here, the hearth is comprised of a motor-driven conveyor, which passes through a series of heat zones, see Figure 2.7.3. The oven is loaded at one end and unloaded at the opposite end. The long flat hearth has thus unlimited flexibility in respect to the size of the baking pans used; the heat in the oven can be controlled easily and accurately at both top and bottom; there is no problem with the stability of the trays and the steam conditions are close to ideal.

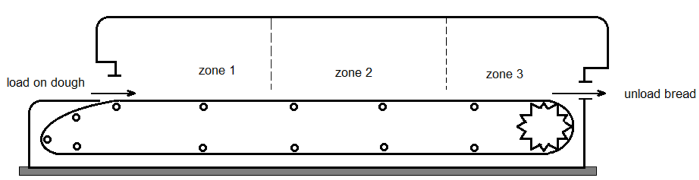


Figure 2.7.3: Schematic diagram of a tunnel-type (redrawn from Pyler 1973)

A *spiral oven* consists of a final steam proofer and oven, both of which allow a continuous wire-grid pan conveyor to pass through them for a specified period of time. The basic design of the proof box and the oven is quite similar, comprising a boxlike structure into which the conveyor enters via an opening near the top; it then descends in a series of spiralling loops around the interior periphery and exits in the lower section.

The three common systems of providing a bakery oven with heat are:

a) *Indirect heating* by combustion gases either conducted through flues and radiators, or flowing past surfaces (e.g. floor and back) of the baking chamber.
b) *Semi-direct heating* in which part of the combustion gases are forced into the baking chamber to create distinct convection currents.
c) *Direct heating* using electricity or gas with ribbon-type burners.

A fourth, indirect, method that utilises high-pressure steam tubes is also used but only to a very limited extent.

The tunnel oven has, according to Mirade *et al*. (2004), two main types of design: direct-fired and indirect-fired.

Direct-fired Oven

Heat is produced inside the baking chamber using wood, gas burners or electric heating elements located above and below the conveyor band. An example of a direct-fired oven is the reel oven, shown in Figure 2.7.1. The heating elements are positioned centrally across the floor of the baking chamber. A baffle placed above the gas burner changes part of the convection heat into radial heat, thereby providing a suitable balance between these two types of heat transfer within the oven.

Indirect-fired Oven

The combustion and baking chambers are separated by steel/fire-brick walls. The baking chamber is usually divided into several zones along the length of the oven and fitted with a chimney. The system requires a burner, combustion tunnel, heater body, radiator tubes and duct recirculation fan. It operates at a negative pressure, to prevent contamination if leakage should occur in the duct. An indirect gas-fired burner system requires 20% more energy than a direct-fired oven. In a typical indirect-heating continuous baking oven, the dough/bread effectively experiences four major heating zones. According to Pyler (1973), the optimum chamber temperature profile is 217, 227, 238 and 232ºC, respectively, along the four zones. Therdthai *et al*. (2002) reported an optimum tin-surface temperature profile of 115, 130, 156 and 179 ºC, respectively, for one particular kind of white sandwich bread.

Semi-direct-fired Oven

A wood-fired bakery oven has a separate baking chamber, which has only one large area in which the dough is placed for baking. A typical wood-fired oven is illustrated in Figure 1.3.1 and described in Section 1.3.

The *heating value* of a fuel (i.e. biomass) can be defined either by the higher heating value (HHV), which is basically its energy content on a dry basis, or by the lower heating value (LHV), which subtracts the energy needed to evaporate water from the HHV. Generally, the solid biomass has a higher heating value on a dry basis: 15.6-20.0 MJ/kg, depending on the species, Klass (2004). The lower heating value is calculated by Eq. 2.12:

$$LHV = HHV^{*}(1-W) - E_{W}^{*}(W + H^{*}{}_{mH_2O}) \qquad \text{Eq. 2.12}$$

HHV is the amount of energy released during complete combustion of dry biomass, Ew is the energy required to evaporate the water contained (2.26 MJ/kg), W is the moisture content, H is the hydrogen content (weight per cent of wet fuel) and mH_2O is the water created per unit of hydrogen (8.94 kg/kg) (Faaij, 2004).

The different heating values of the fuels originate from differences in the chemical composition of their basic components, i.e. cellulose $(C_6H_{10}O_5)_n$, hemicelluloses $(C_5H_8O_4)$ and lignin $(C_9H_{10}O_3)_{(0.9\text{-}1.7)m}$. Sulphur, nitrogen and ash are also present in the fuel but to a lesser extent. The content of moisture is usually 50–60% in green wood and 20–35% in dry wood (Tsamba, 1994 and Klass, 2004). The elementary composition of *micaia*, the wood most commonly used in Mozambique, is shown in Table 2.

Table 2. The Elementary composition of *micaia* wood (Tsamba, 1994)

Components (%m/m)	**Moisture Base**	**Dry Base**
Moisture (W)	9.5	-
Ash (A)	1.72	1.9
Sulphur (S)	0.02	0.02
Carbon (C)	44.62	49.3
Hydrogen (H)	5.34	5.90
Nitrogen (N)	0.36	0.40
Oxygen (O)	38.44	42.48
HHV (MJ/kg)	17.36	19.18
LHV (MJ/kg)	15.96	17.88

In general, the *moisture content* represents the amount of the water in relation to total weight.

Density is defined as the mass per unit volume of a substance. Knowledge of the density of wood, which varies with moisture content and specific gravity, is useful for estimating shipping weights. The water content can affect both mass and volume; the specific gravity is the density of the substance relative to the density of water (Cuvilas, 2009).

Ash is an inorganic residue remaining after wood has been combusted at high temperature. The amount is usually <1% for wood from temperate zones and >1% for wood from tropical zones such as Mozambique, (Petterson, 1984), where it can reach up to 14% (Tietema *et al., 1991).*

Biomass is preferred over fossil fuels with respect to contributing to a sustainable society, although its utilisation in small scale applications undeniably causes some pollution, e.g. by the formation of particles. Combustion can ideally be defined as being a complete oxidation of the fuel characterised by a two-step process, consisting of an initial conversion of the solid fuel to gaseous compounds (also known as gasification products), which is followed by gas phase reactions. Optimisation of the fuel being used and the rates of air flow in the combustion process, together with mass and energy balances are necessary to minimise the amount of fuels consumed and to satisfy the process and environmental constraints (Mancuhan and Kucukada, 2006). The oxidation of biomass consists of several basic steps: drying, pyrolysis, gasification and, finally, full combustion. Biomass is never totally dry; any water in the fuel will be evaporated. The higher the moisture content, the more energy required for its evaporation. This is an important parameter in the overall performance of the system.

Pyrolysis: Devolatilisation and pyrolysis are two of the major decomposition processes that can affect a particle of wood. Their detailed kinetics remains unknown due to their complexity in both the reaction paths and generation of products. Therefore, the interpretations of experimental investigations are restricted to global mechanisms. Several, and quite varying, modes of pyrolysis have been presented in the literature, as shown by e.g. Faaij (2004), Bruch *et al.* (2003), Peters and Bruch (2001) and Oman *et al. (1999)*. Pyrolysis models for wood can be arranged into different groups, according to their complexity: a one-step model, models with competing reactions and models with secondary reactions.

Gasification and combustion: Conversion due to the gasification and combustion of a solid particle involves a heterogeneous reaction which, apart from the chemical kinetics, always includes the transport of at least one species. Hence, the process of a heterogeneous reaction may be divided into the following steps:

i) Transport of one or more reaction parameters
ii) Adsorption at active sites
iii) Chemical reaction
iv) Desorption of the products of the chemical reaction
v) Transport of one or more products

In this sequence, the overall rate of the entire process is determined by the slowest of these steps, which usually involves a strong temperature dependence (Peters and Bruch, 2001).

Biomass is a highly reactive fuel compared to coal and has a much higher content of oxygen, a higher hydrogen-to-carbon ratio and a higher content of volatile substances. The bulk composition of biomass in terms of carbon, hydrogen and oxygen (CHO) does not differ much between various sources of biomass: typical (dry) weight percentages for C, H and O are 45–50%, 5–6% and 38–45%, respectively. The content of the products (lighter components that are released during the pyrolysis stage in particular) can vary between 70 and 85%. The latter is typically higher for non-woody and "younger" greener sources of biomass - (Faaij, 2004 and Klass, 2004).

The air-to-fuel ratio is expressed as the mass of air (kg) used to burn a unit of fuel (kg). It is important for achieving efficient combustion. In general, the overall air-to-fuel ratios in virtually all combustion applications are higher than the theoretical chemical-reactant (stoichiometric) ratios needed. The stoichiometric air-fuel ratio $(a/f)_s^v$ in kmol/kg wood for the complete combustion of fuel having the average composition of carbon, x_c, hydrogen, x_h and oxygen, x_o can be found in Eq. 2.13.

$$(a/f)_s^v = \frac{1}{0.21}\left(\frac{x_c}{12} + \frac{x_h}{2} - \frac{x_o}{32}\right) \qquad \text{Eq. 2.13}$$

In order to guarantee the complete combustion of solid fuels, an excess of 50% air is recommended (Ghojel, 1998). This amount can be reduced depending on the type and characteristics of the fuel and the design of the combustion equipment. For industrial boilers, the amount of excess air required to burn natural gas efficiently is about 5%, for oil around 10–15% and for pulverised coal around 20–25%. These amounts represent the amount of excess air required to ensure that all of the fuel molecules are able to find oxygen molecules with which to react. For small-scale industrial wood burners, on the other hand, the recommended amount of excess air is not well defined; well-engineered systems are nevertheless found to operate in the range of 50–100% excess air. Normally, the amount of excess air necessary for practical use can be identified by the rapid decrease of the slope in a graph of the exhaust emissions of carbon monoxide versus the air-to-fuel ratio.

The thermal efficiency of a device can be based on steady or unsteady state operations or on the specific consumption of energy, the latter being defined as the amount of energy input required performing a given task. Equation 2.12 expresses the specific coefficient (SC):

$$SC = \frac{mass\ of\ fuelwood\ consumed}{mass\ of\ bread\ baked} \qquad \text{Eq. 2.14}$$

The relationship between SC and cooking efficiency is shown in Eq. 2.15:

$$\eta_{cooking} = \frac{1}{SC} \cdot \frac{C_{pf} \cdot \Delta T}{HHV} \qquad \text{Eq. 2.15}$$

where C_{pf} is the heat capacity of the specific food and *HHV* is the higher heating value. Due to the fact that the evaporated water is not condensed in these types of combustion units, it is, however, recommended that the lower heating value (LHV) be used rather than the HHV.

A compromise has to be reached between the control and the performance of the entire combustion process (which includes costs, efficiency and emissions). On the one hand, there are various technical variables, such as the design of the equipment, the materials used, the methods of feeding in both air and fuel and strategies of control; on the other hand, a number of process variables, such as the transfer of heat, the residence times, the insulation of excess air and the properties of the fuel (i.e. moisture, mineral fraction and composition) must all be balanced to obtain the desired performance (Faaij, 2004).

There are several fuels that are suitable for use in these ovens, including fuel oil, natural gas, softwood and hardwood, as shown in Table 4. The energy released during combustion is indicated by the heating value of the fuel, which is the energy per unit of the fuel.

Table 4: Theoretical volumetric energy density heat values of different heat sources (Pyler, 1973)

Supply	***Heat generated***	***Units (SI)***
Fuel Oil (heavy)	44 592.0	*MJ/m*^{3}
Fuel Oil (light)	39 000.0	*MJ/m*^{3}
Natural Gas	39.0	*MJ/m*^{3}
Propane-Butane	21.5	*MJ/m*^{3}
Manufactured Gas	1 100.0	*MJ/m*^{3}
Hardwood (air dried)	8 854.0	MJ/m^3
Softwood (air dried)	5 411.0	MJ/m^3
Mixed Hardwood (air dried)	7 234.0	MJ/m^3

Electricity, although cleaner and easier for maintenance, is expensive. Generally, 1 kg of bread requires 359–475 kJ to complete a baking cycle. In additional, approximately 95 kJ/kg is needed to heat the tins and to compensate for heat lost via the walls of the oven.

3. METHODOLOGY

3.1. Analysis of Bakeries in Mozambique

The methodology was divided into two different parts: the survey consisted of pre-audit and detailed audit and laboratorial analyses to perform the same quality parameters of the bread produced in wood-fired bakeries that are directly influenced by baking temperature.

3.1.1. Pre-Audit

The review of the available literature pertaining to the demand of biomass in the townships of Maputo and Matola was taken. An inventory, (i.e. pre-audit) and detailed audit, was used to collect specific information regarding the equipment and bread baking process including the overview of wood consumption in the wood-fired bakeries. The information was collected from a production manager and/or from a shift team leader.

3.1.2. Detailed Audit

The detailed audit ovens were selected randomly among ovens with average size (3m diameter), assuming 95% confidence interval, 99% of the response and 5% margin of error. Eleven semi-direct bakeries were found to be the minimum sample in a universe of 46 (number of ovens with 3 m diameter). To increase the precision, the detailed audit consisted of 15 semi-direct ovens. In addition to this, three indirect bakery ovens (one with three and two with four drawers) were used as a reference in this research. The following parameters were determined: the dimension of the bakery furnaces, the weight of the wood and its combustion time, the temperature profile of the bread during the baking process, the temperature in the combustion and baking chamber and, finally, the temperature profile of the chimneys. The temperature was measured every 3-seconds in the fire-grate, mixing box and three different points in the combustion ducts in semi-direct wood-fired bakery ovens (labelled fire-grate, mixing box, position 2, 3 and 4 in Figure 3.1.1A) during the 4 h period using N-type thermocouples. The thermocouples were placed in the conducts that connect the wood combustion chamber and the main conduct to measure the temperature of the flow. This procedure reduces the impact of radiation during the measurement. A K-type thermocouple was used to measure the fire-grate and baking temperature, the temperature at the top, bottom and centre (crumb) of the sample of bread and in position P1 and P2 to evaluate the temperature distribution in the oven as illustrated in Figure 3.1B. The thermocouples, which had first been calibrated with boiling water, were connected to a data logger (DATA LOGGER T3000) and recorded measurements every 2 min during the allocated time. Their displacement during the expansion of the bread in the baking process meant that the exact position of each thermocouple had to be measured after the bread had cooled down.

The thermal efficiency of the oven is calculated by the equation 2.14 and 2.15 described in section 2.7.

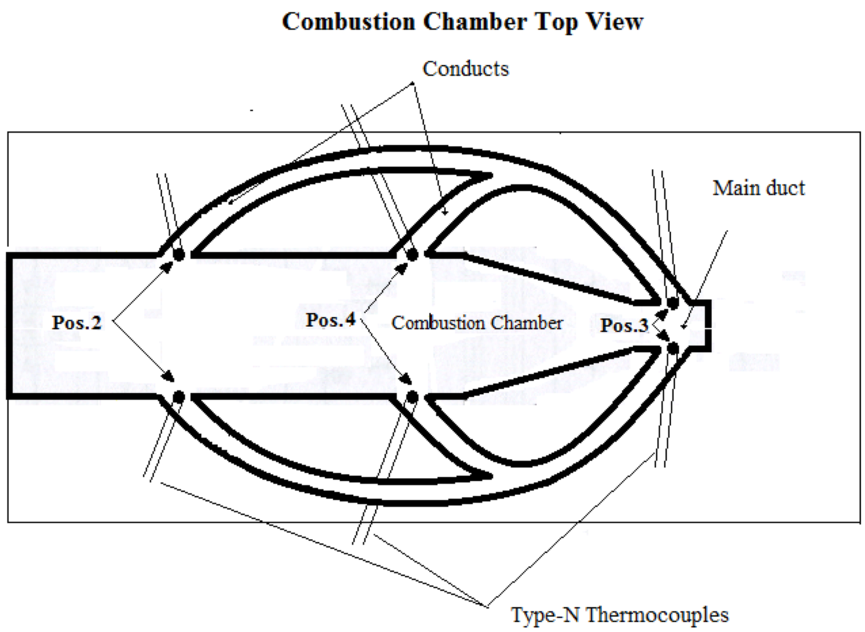


Figure 3.1.1.A: Schematic representation of the position in which the combustion temperatures were measured.

3.1.3. Analysis of the temperature of the baked bread

The analysis of the final product, including the colour of the crust, the temperature of the crumb and the moisture content, was undertaken to study the influence of baking temperature and time. The weight loss (change in moisture content) was determined by weighing samples before and after water evaporation at 105°C immediately after the baking process was completed (technical scale B-3000 ±o.5 g). Water activity (a_w) or water stability was evaluated by measuring the water content of the bread when it was newly baked and again after a number of days conservation under external conditions (Aqua lab equipment).

With the aim of predicting and controlling the development of the browning during the baking, it is necessary to quantify the advance of the underlying reactions. The formation of colour can be measured by different techniques. They can be divided into two main categories: direct and indirect techniques. The direct methods aim to measure the concentration of browning reaction products and the indirect approach is focused on registering the variation of colour (Purlis, 2010). In this work, the colour of the crust was determined using a Colour Reader Minolta CR with an L-a-b system; the response was expressed as the lightness (L) of colour. The measuring area is 8 mm. All measurements were taken under the conditions of standard illuminate D65 and 10° observer.

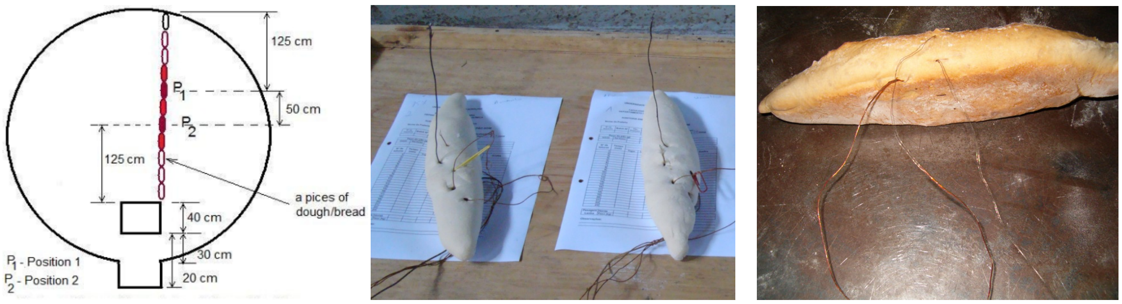


Figure 3.1.1.B: Schematic representation of the positions of the loaves in the baking chamber and the techniques used to study the temperature profile in the bread baking process (dough and bread, respectively)

3.2. 2D Physical Model

A two dimensional model was constructed to visualise flows in various equipment, including the baking chamber of a wood-fired bakery oven. It was performed to achieve qualitative information and measurements of the flow characteristics (Figure 3.2.1). The first step was to design a physical model relative to the real equipment (scale 1:10). An aluminium plate with a thickness of two millimetres and width of five millimetres was used for the two-dimensional model arranged on a horizontal plate in a water table. Three valves controlled the velocity of the recirculation water in the model, and aluminium powder (with a diameter of about 40 μm) was used to visualise the flow pattern. The material does not dissolve in water and it has a high reflective factor and colour; therefore, it can be reused almost indefinitely. The disadvantage of the powder is that it tends to sink at long running times. It was possible to obtain the streamline pattern by allowing fairly long exposures time, on ASA 100 films, as shown in Table 5. If the primary aim of the model is flow visualisation, it is important that there is clear access to the areas of interest.

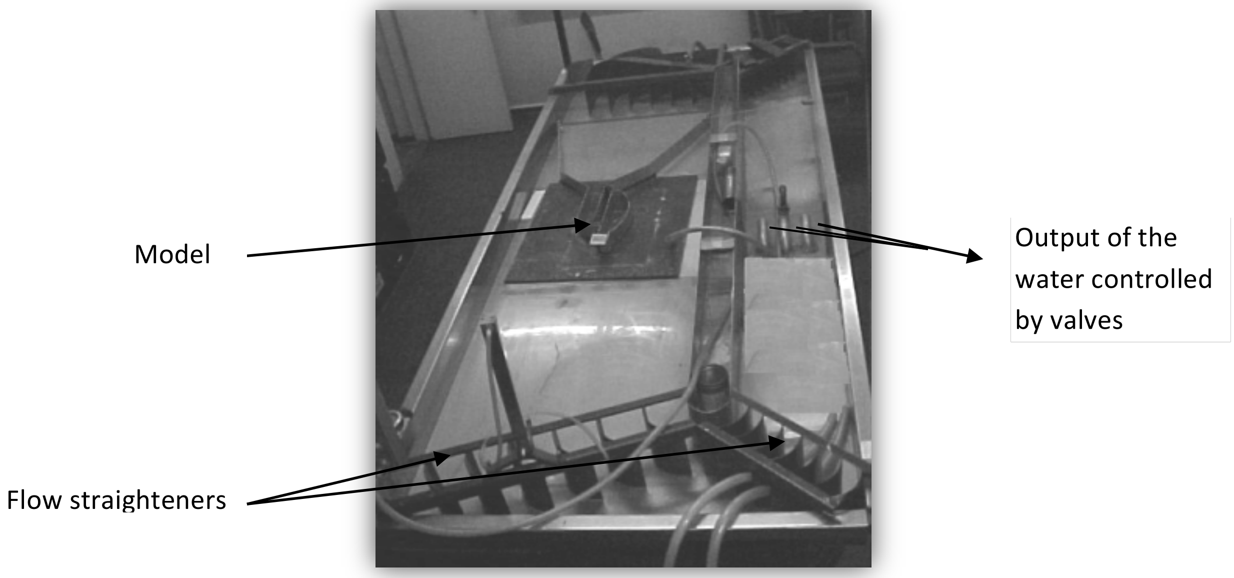


Figure 3.2.1: The bi-dimensional water table used in the physical simulation studies.

Table 5: The experimental parameters employed in the bi-dimensional experiments

Water velocity [m/s] at the model inlet	0.020			0.023			0.030			0.038		
Regulation of light	5.6	8	11	5.6	8.0	11	5.6	8	11	5.6	8.0	11
Exposure time (s)	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4
	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8	1/8
	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15

The velocities were calculated from a typical wood consumption in wood-fired bakery ovens (18 kg/h); the amount of excess air varied between 2 and 4, which is common in poor combustion conditions (Lucas *et al.,* 2000 and Nussbaumer, 2003). In the velocity calculations, it was assumed that the combustion of wood was complete and that atmospheric air entered by natural convection to the combustion chamber.

3.4. Construction and Experiments on *In-Situ* Bakery Oven

3.4.1. Construction of In-Situ Bakery Oven

An *in-situ* bakery oven has been built at the Eduardo Mondlane University in Mozambique. It is equipped with the points that permit the following measurements to be taken: the temperature distribution along the whole oven, the composition of the gases in the middle (i.e. the inlet of the baking oven) and the outlet of the chimneys and the distribution of heat during the baking process. Figure 3.4.1 shows the complete oven as it was built as well as the positions prepared for the thermocouples.

1) The temperature in the oven can be measured by inserting copper tubes with a diameter 5 mm in the previous position of the probes, as shown in Figure 3.4.1 b). The aim is to insert thermocouples of K and N types to measure the temperature and then compare the measurements with the CFD model.

2) An arrangement of probes in the main outlet through which the hot gases leave the combustion chamber on the way to the baking oven as well as at the bottom of the chimneys in order to analyse the composition and temperature of the gas.

3) Thermocouples on the bottom of the baking oven are distributed in such a way as to measure the temperature along the base.

4) Appropriate equipment allows the heat flux to be measured.

Figure: 3.4.1:a) General view of the *in-situ* bakery oven.

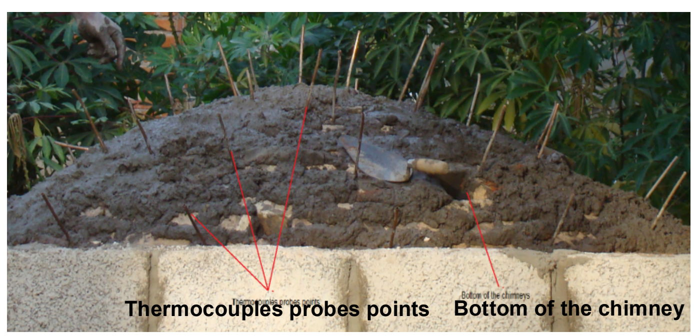


Figure: 3.4.1:b) The distribution of the probes along the baking chamber.

3.4.2. Measurements in the in situ Bakery Oven

Experimental measurements were done during the baking process. Specific emphasis was paid to the temperature distribution in the different parts in the oven, the air flow rate and the wood that was used. Five types of wood were burnt and was done in two parts: the first used just one species, Red Mikaya (Acaceas Sp.), whilst the second used Mikaya, Mbeswu and Nala (Albizia Versicolour, Moprus S and Acaceas) and one local species known as Xihoho.

Temperature Measurement

The temperature was measured every 10 seconds during 24 h at several points in a WFBO to obtain a realistic idea of the temperature distribution within it. Twelve N-type thermocouples were used to measure the temperature in the combustion chamber and the ducts between the combustion chamber and the baking oven; eight K-type thermocouples were used to measure the temperature in the baking oven and the chimneys, Figure 3.4.2A and B. Thermocouples were connected to the *Data logger K2700*.

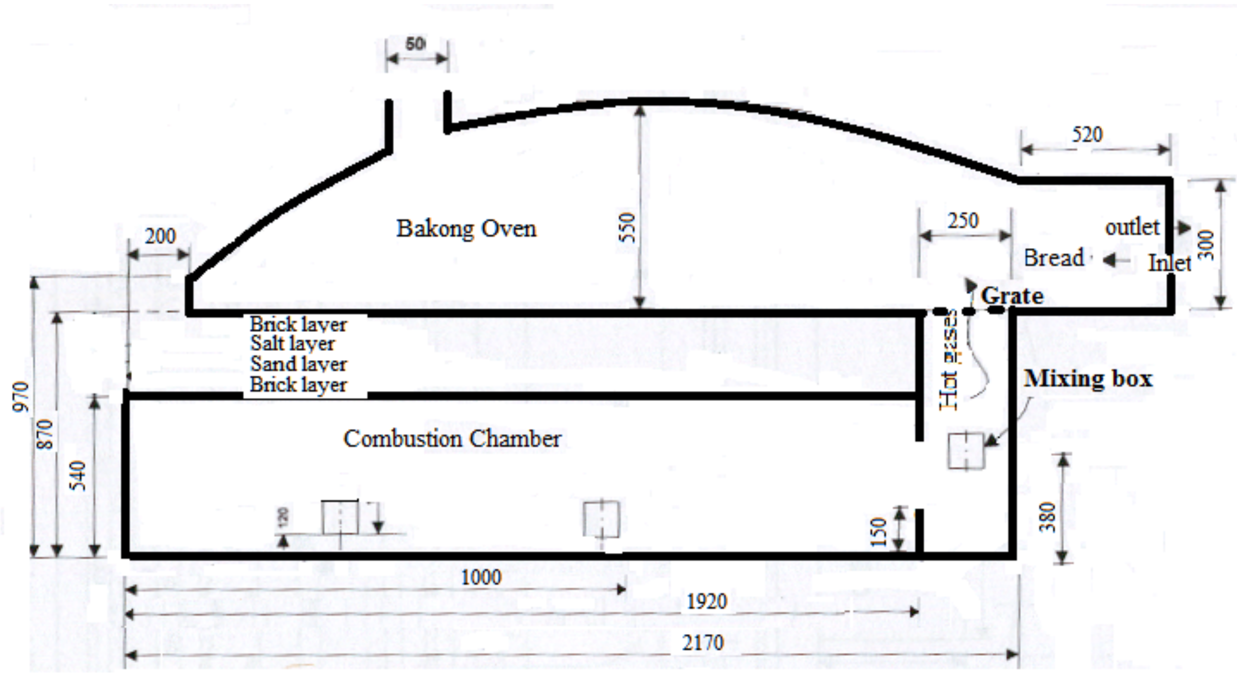


Figure 3.4.2: A. The technical design of the wood-fired bakery oven by taking a longitudinal cut at the central section of the WFBO.

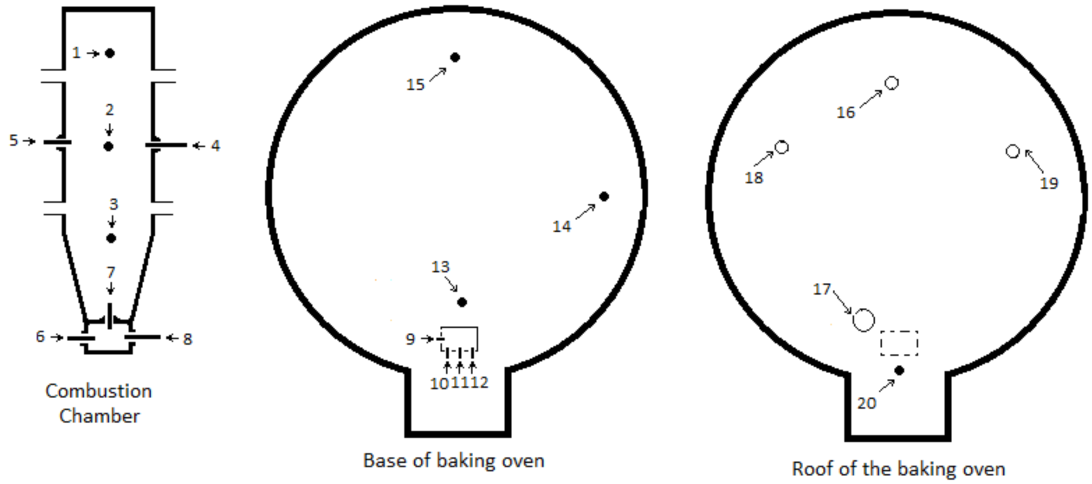


Figure 3.4.2: B. Location of the thermocouples in the WFBO.

Thermocouples 1, 2 and 3 were placed at top of the combustion chamber, 4 and 5 were placed at the entrance of heat distribution pipes that are connected to the junction, 7 was placed at the hole that led to the duct and 6 and 8 were located at the junction of the duct (mixing box) that leads out of the combustion chamber with main duct (grid). Thermocouples 9, 10, 11 and 12 were placed around the grid, at the base of the baking oven; 13, 14 and 15 below the brick layer of the oven base; 16, 18 and 19 were placed in the oven chimney and 17 in the grid chimney and 20 was placed on the roof of the baking oven.

An energy balance performed at a thermocouple junction at temperature T_c exposed to gas at temperature T_g and surrounding walls at T_w yields the following relationship:

$$T_g - T_c = \frac{\rho_c C p_c d}{4h}\frac{\partial T_c}{\partial t} + \frac{k_c d}{4h}\frac{\partial^2 T_c}{\partial x_c^2} + \sigma\varepsilon(T_w^4 - T_c^4) \qquad \textit{Eq. 3.1}$$

The difference between the temperature of the gas and the thermocouple reading is due to the transient response of the thermocouple (first term on the right hand side of the equation), the transfer of conduction heat along the thermocouple (second term) and the radiation heat transfer with the surroundings (third term). In the present case, the fresh blank thermocouples with low emissivity was used to minimise the effect of radiation and also due to the more and less high flow rate of the hot gases from the combustion chamber to the outlet grid that leads to the baking oven. Four thermocouples were placed 5 cm below the fire-grid leading into the baking oven to measure the temperature of the incoming hot gases. The temperature profiles with the mass flow rate of the hot gases represent the total energy that is useful in the baking process and were used to validate the computational model.

Parameters of the wood

The moisture content, ash, density and heat values of the five different species of wood were determined. The moisture content was found by weighing each sample before and after they were placed in the oven (Oven Model-295) for a 5 h period at 105°C. The heat values were determined using a bomb calorimeter (IKA C200). The ash content was obtained by examining the difference in the weight of the samples after combustion in a muffle furnace (Cabolite S336 RB) for 5.5 h at 550°C. The densities were based on the volume and weight measurements of the samples. The volume was determined using a known amount of fine sand. The amount of wood used was determined by weight.

Velocity

The inlet velocity into the combustion chamber was estimated using a flow meter (Flow Meter AB 2050) inserted in a hole with diameter of 0.065 m placed 0.70 m from the combustion chambers door to avoid high temperature, as shown in Figure 3.4.3.

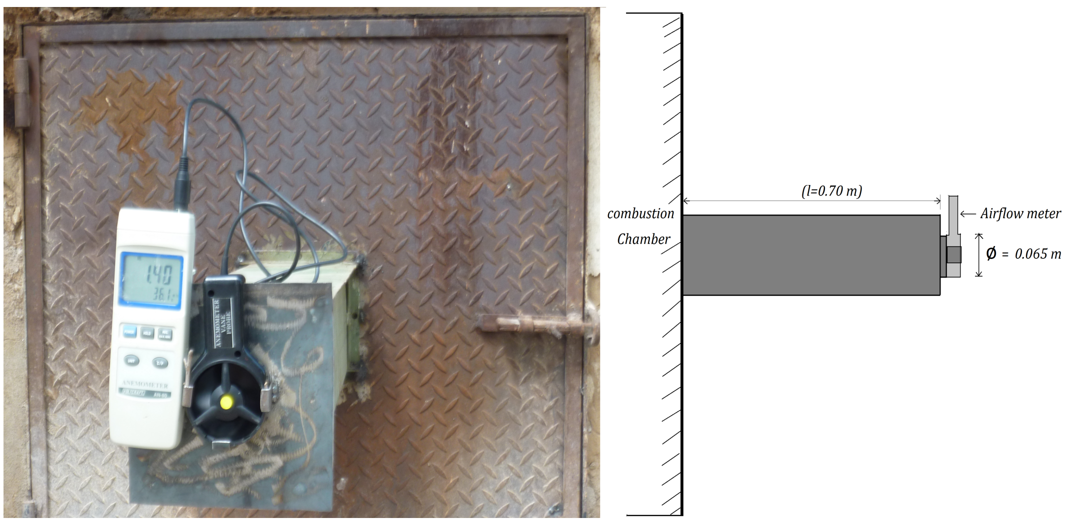


Figure 3.4.3: Measurement of the airflow entering the combustion chamber. Left: a photograph. Right: the arrangement.

Parameters of the bread quality

The analysis of the bread quality is based on comparison of the different parameters (moisture content, colour of the crust and the crumb, water activity and the mould) that were evaluated during the bread baking process. The comparisons are made between the breads baked at different positions of the same or different batches.

The analyses were done with respect to moisture content, colour, water activity, and mould evaluation during the shelf life. The moisture content was evaluated using an oven at 105°C during 5 hr. The colour was evaluated via Colour Reader Minolta CR10 with an L-a-b system. The water activity was evaluated with Aqualab Serie 3 TE made in USA. The mould was evaluated by visual inspection of the area affected compared with non-affected bread. The procedures used to evaluate these parameters were described in detail earlier (Manhica *et al.,* 2012a). Figure 3.4.4 shows the different positions that were used for the various bread samples.

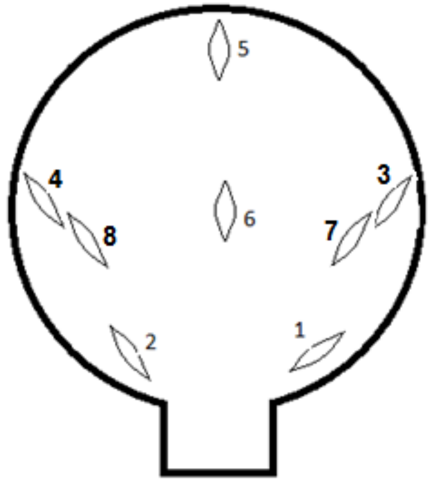


Figure 3.4.4: Location of the samples within the oven.

3.5. Mathematical Models

The governing, fundamental, equations are the conservation laws of mass, momentum, energy and species (e.g. Thunman *et al*. (2002), Bruch *et al.* (2004), Bruch *et al. (*2003), Miltner *et al*. (2006), Hostikka *et al. (*2001), MacGrattan *et al.* (2004), and Wang *et al*. (2008)).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho u = 0 \qquad \textit{Eq. 3.2}$$
$$\frac{\partial}{\partial t}(\rho Z) + \nabla \cdot \rho Z u = \nabla \cdot \rho D \nabla \mathrm{Z} \qquad \textit{Eq. 3.3}$$
$$\left(\frac{\partial u}{\partial t} + \frac{1}{2}\nabla |\mathrm{u}|^2 \right) + \nabla \tilde{p} = \left((\rho - \rho_\infty) g + \nabla \cdot \tau\right) \qquad \textit{Eq. 3.4}$$
$$\rho c_p \left(\frac{\partial T}{\partial t} + u \cdot \nabla \mathrm{T}\right) = \dot{q}''' - \nabla \cdot \mathrm{q_R} + \nabla \cdot k \nabla T \qquad \textit{Eq. 3.5}$$

where ρ, u, Z and T are the density, velocity vector, mixture fraction and temperature, respectively. D is the diffusivity, $\tilde{p}$ the perturbation pressure, τ the viscous stress tensor and *k* the thermal conductivity. $\dot{q}'''$ and $-\nabla \cdot \mathrm{q_R}$ are the source terms due to the chemical reactions and radiation, respectively. These equations are supplemented by an equation of state, namely:

$$p_0 = \rho \boldsymbol{R} T \textstyle\sum_i Y_i / M_i \qquad \textit{Eq. 3.6}$$

where the pressure is replaced by an average pressure p_0 to filter out the acoustic waves. ***R*** is the ideal gas constant and Y_i and M_i are the species mass fraction and moles mass. p_0 is constant unless the domain is tightly sealed, in which case it depends only on time.

Turbulent flow without any chemical reaction was assumed in order to approximate the flow of hot gases from the combustion chamber to the baking section in the oven. The turbulent flows are characterised by fluctuating velocity fields primarily due to the complex geometry and/or high flow rates. The Navier-Stokes equations can be solved directly for laminar flows but, for turbulent flows, the direct numerical simulation (DNS) with full solution of the transport equations at all lengths and time scales is too computationally demanding, since the fluctuations can be of small scale and with a high frequency, i.e. the Re number is below 5000, (Andersson, *et al*., 2009). An alternative is, therefore, to transform the Navier-Stoker equations on the small eddies instead of directly simulating the Reynolds averaging and filtering processes (Wang *et al.,* 2008). The Reynolds-averaged Navier-Stokers (RANS) equations represent transport equations for the mean flow quantities only and are developed by dividing the instantaneous properties in the conservation equations into the mean and fluctuating components, as shown by:

$$\phi = \bar{\phi} + \phi' \qquad \textit{Eq. 3.7}$$

The most common RANS models employ the Boussinesq (eddy viscosity concept, EDC) to model the terms of Reynolds stresses (Andersson *et al.*, 2009 and TorII *et al.,* 1989). The hypothesis states that an increase in turbulence can be represented by an increase in effective fluid viscosity, and that the Reynolds stresses are proportional to the mean velocity gradient by this viscosity. Models based on this hypothesis include e.g. Spalart-Allmaras, standard k-ε, RNG k-ε, Realizable k-ε, k-ω and its variants (Fluent 6.1 User's Guide, (2004)).

In order to mimic a wood-fired bakery oven, the selected model must be able to handle low Re numbers and still include the turbulence, which due to the complex geometry involved, causes fluctuation in the velocity fields. A mathematical model that can be used to describe the flow pattern in these conditions is the two-equation k-ω model, where the turbulence specific dissipation, ω, is used as a length-determining quantity. This quantity is defined by $\omega \propto \varepsilon / \kappa$, and it should be interpreted as the inverse of the time scale on which dissipation occurs. The model k-equation is:

$$\frac{\partial \kappa}{\partial t} + \langle U_j \rangle \frac{\partial \kappa}{\partial x_j} = \nu_T \left[\left(\frac{\partial \langle U_i \rangle}{\partial x_j} + \frac{\partial \langle U_j \rangle}{\partial x_i} \right) \frac{\partial \langle U_i \rangle}{\partial x_j} \right] - \beta k \omega + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_k} \right) \frac{\partial \kappa}{\partial x_j} \right] \qquad \textit{Eq. 3.8}$$

and the modelled ω-equation is:

$$\frac{\partial \omega}{\partial t} + \langle U_j \rangle \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{\kappa} \nu_T \left[\left(\frac{\langle U_i \rangle}{\partial x_j} + \frac{\langle U_j \rangle}{\partial x_i} \right) \frac{\partial \langle U_i \rangle}{\partial x_j} \right] - \beta^* \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] \qquad \textit{Eq. 3.9}$$

The heat balance is written as

$$\frac{\partial(\rho c_p T)}{\partial t} = -U_j \frac{\partial(\rho c_p T)}{\partial x_j} + k_{eff} \frac{\partial^2 T}{\partial x_j \partial x_j} - P \frac{\partial U_j}{\partial x_j} + \tau_{ij} \frac{\partial U_i}{\partial x_j} + S_T \qquad \textit{Eq. 3.10}$$

where the turbulent viscosity is calculated from $\nu_T = \frac{\kappa}{\omega}$.

One advantage this model has over the more commonly used k-ε model is that it can predict the viscous sub layer near the wall more reliably, thereby eliminating the need to use wall functions except for computational efficiency. However, the low Reynolds k-ω model requires a very fine mesh close to the wall, with the first grid below y^+=5.

2D Modelling Assumptions

Two-dimensional flow: The computational time was reduced by taking a 2-D cross-section, vertically and longitudinally, with the centre of the oven as the calculation domain. Effective heat conductivity was used to include both the brick layers and the covering sand in order to simplify the geometry further.

Turbulent flow: The irregular, but natural convection of the air flow, coupled with the complex geometry, meant that turbulent flow was assumed, in spite of the low Re number (Hostikka *et al.,* 2001 and Nussbaumer, 2003).

Steady state: The system was assumed to be in a steady state so that the cold flow physical model could be compared with the mathematical model.

Boundary Conditions

At the combustion chamber: The combustion chamber was only included in the modelling to provide a realistic flow pattern in the bakery oven. A reaction was therefore not modelled in this chamber; the heat released during combustion was instead used to increase the temperature of the incoming atmospheric air. It was assumed that the incoming air had a temperature of 1500K, which satisfies the temperature range of 770–850 K measured experimentally on the fire-grate leading into the baking chamber of the common bakery oven, when using an amount of excess air between 2 and 4 (Nussbaumer, 2003). The decreases of temperature is due to heat being lost through the walls and at the top side of the feeding door. The velocities were calculated from the stoichiometric amount of air required to combust the incoming wood (18 kg wood /h); the volume of air was based on the theoretical amount needed for combustion and the different ratios of excess air. The velocities used are shown in Table 6.

The experimental temperature measurement was performance in one selected point (around 0.1m of start point) in the fire-grate as described by Manhica *et al.,* (2012a).

At the wall surfaces: Convective and radiative heat transfer boundary conditions were applied to all outer walls and to the feeding door. Heat flux to the wall was computed as

$$q = h_f\left(T_w - T_f\right) + q_{rad} \qquad \text{Eq. 3.11}$$

h_f is the local heat transfer coefficient of the fluid (W/m^{2}K), T_w is the wall surface temperature (K), T_f is the local fluid temperature (K) and, q_{rad} is the radiative heat flux (W/m^2). Air, which consists of nitrogen, oxygen, small amount of carbon dioxide and other gases, has been found as not showing absorption band in those wavelength regions of importance to radiant heat transfer. The walls are insulated with red bricks (0.22 m). The relative velocity between the wall and the fluid is set at zero, i.e. non-slip condition. The Reynolds number, velocity and shear close to the wall are modelled using a wall function, y+. The heat loss, which was calculated from the overall heat transfer coefficient that combines convection and conduction, was estimated as being approx. 13.0 W/m^{2}K (Birds *et al.,* 2001).

Together with the initial boundary conditions (velocity, and temperature), the equations were solved with Fluent on ANSYS 12 Workbench. It was found that 1500 iterations were satisfactory to achieve low residuals for all of the equations. At the end of the iterations, the residuals were reduced to less than 10^{-3} of their initial values. Simulations were carried out to study how the airflow patterns were affected by air, that is, air that enters the combustion chamber in wood-fired bakery ovens at different velocities.

Table 6: The velocities used in the different experiments and the corresponding Re number. Density = 0.23 kg/m3, viscosity = 0.46·10-4 kg/mK, characteristic length of the inlet section of the combustion chamber = 0.54 m.

Parameters /Units	Simulation #1	Simulation #2	Simulation #3	Simulation #4	Simulation #5	Simulation #6
Velocity, v_i [m/s]	0.30	0.40	0.45	0.59	0.63	0.74
Re number	$81 \cdot 10$	$11 \cdot 10^2$	$12 \cdot 10^2$	$16 \cdot 10^2$	$17 \cdot 10^2$	$20 \cdot 10^2$

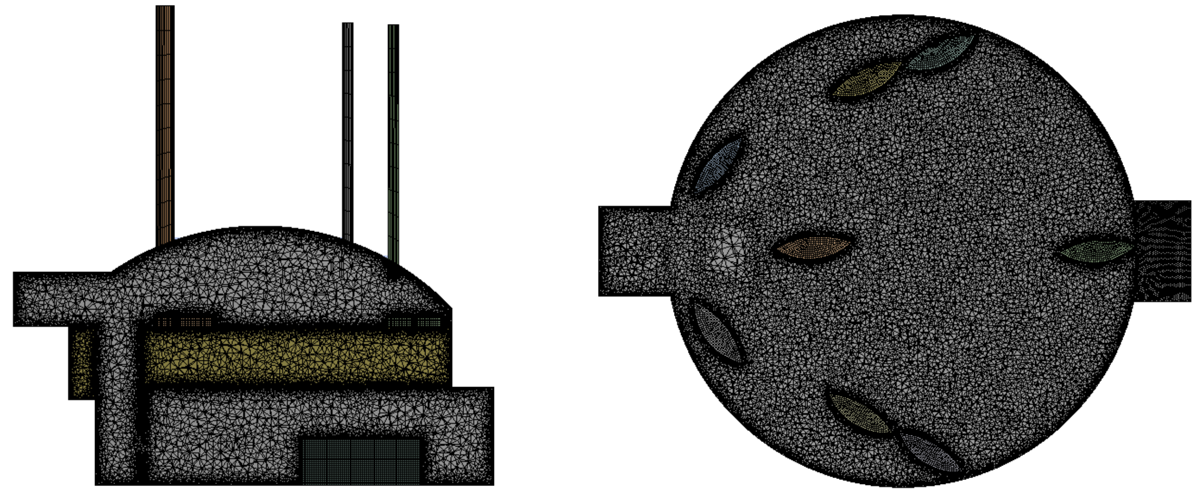
The effect of the feeding door was calculated using a model that considers parallel simulation with an inlet-vent as a boundary condition.

3D Mathematical Model

Modelling Assumptions

A full 3D model of the oven was used as calculation domain. A wall consisting of layers of brick-sand-salt-brick was used in order to study the influence of heat, transferred from the top of the combustion chamber to the base of the baking oven. The heat transfer through the remaining outer walls of the oven was estimated by the brick thickness.

The geometry was drawn and meshed with ANSYS 15. The irregular geometry, structured by curvilinear grid arrangements, meant that it was considered to be complex (Versteeg and Malalasekera, 2007). It was therefore sub-divided into blocks, and inflation was used to assist the adequate mesh of the geometry into a cylindrical structure.



a) b)

Figure 3.4.5 – Illustration of sub-division (blocks) used to assist the adequate mesh in the model

Turbulent flow: The irregular and natural convection of the air flow and the complex geometry meant that the flow can be considered turbulent, in spite of the low Reynolds number (Hostikka *et al.,* 2001 and Nussbaumer, 2003).

Steady state: Steady state modelling was used to achieve the conditions of an empty oven (Model 1). This was then used as the surrounding condition when bread was introduced (Model 2), on which the transient calculation could be based. Even though there are fluctuations in the combustion chamber, the system in the oven was assumed to be steady state due to an almost constant temperature across the fire-grate to the baking oven.

Transient: Transient condition is used to calculate the temperature variations in the bread to simulate the baking process (Model 2). The bread samples were located at exactly the same place as those studied in experiments carried out by Manhica *et al.* (2013), Figure 3.4.4. The baking process in Model 2 was simulated by assuming an identical flow pattern in the oven as in the steady state case (Model 1). In the steady state condition of Model 2, the bread was placed inside the oven at an initial temperature of 300 K and a dynamic calculation was performed for 20 minutes, which equals the average baking time. The average temperature of each loaf of bread was recorded every minute to evaluate the heat transfer process. The heat capacity and thermal conductivity of the dough/bread is dependent on temperature, and a piecewise first order polynomial was used according to Wong *et al.* (*2007),* Table 7. The scattering coefficient is of little relevance to the baking process and was thus assumed to be zero.

The absorption coefficient: The absorption coefficient in the gas was evaluated, including water vapour released from the dough during the baking process. Due to the low temperature in the oven walls, the radiation wavelength was above 2 μm and absorptions or emissions of radiative energy by the gas were neglected.

Table 7. Dependence on bread properties with temperature.

Source: Wong *et al., 2007*.

Temperature (K)	*Heat Capacity (J/kg K)*	*Thermal Conductivity (W/m K)*
301	3080.0	0.85
333	2550.6	0.38
393	1717.3	0.17
500	1514.1	0.16

Boundary conditions

The combustion chamber was only included in the modelling to provide a realistic flow pattern in the bakery oven. Therefore, the heat released during combustion was modelled as a heat source in the combustion chamber to increase the temperature of the incoming atmospheric air (298 K). The temperature had a range of 600–700 K measured experimentally on the fire-grate leading into the baking chamber during the baking process of the *in situ* WFBO. The heat lost through the wall of the combustion chamber was evaluated using conduction by the brick wall with a thickness 0.16 and 0.22 m, respectively. The thickness of the chimney wall was 0.005 m whilst the thickness of the steel feeding door was 0.003 m.

The inlet velocity was found to be 0.0123 m/s. This is an average of the experimental measurements of the air flow through the hole of diameter 0.065 m into the entire hydraulic diameter (0.695 m) of the combustion chamber (Manhica *et al., 2013*).

At the wall surfaces, the heat flux to the wall was computed as:

$$q = h_f A\left(T_f - T_c\right) - \sigma\varepsilon A T_c^4 + \sum_\kappa \sigma\varepsilon_\kappa A_\kappa \alpha_\kappa T_\kappa^4 \qquad \text{Eq. 3.12}$$

where h_f is the local heat transfer coefficient of the fluid (W/m^{2}K), A is the area of the wall, T_c is the surface temperature (K) of the wall, T_f is the local temperature (K) of the fluid, σ is the Boltzmann coefficient and ε is the emissivity coefficient. The relative velocity between the wall and the fluid is set at zero, i.e. non-slip condition. The Reynolds number, velocity and shear close to the wall are modelled using a wall function, y+.

Emissivity at the walls and surface of the bread: The emissivity of the brick walls was taken as being 0.75, which is accurate from 900 to 1200 K (Wong *et al.,* 2007). The emissivity of the bread varies from 0.4 to 0.8, so 0.6 was used because, according with experimental results (Rek *et al.,* 2012), no influence is exerted by the surface temperature of the bread during the baking process.

Numerical Simulation

The 3D CFD model was used to study the heat transfer during the baking process to predict the differences in the quality of bread baked in the same batch. The effects of the design of the oven with respect to velocity, temperature distribution and heat transfer during the baking process were analysed. This was used to find an improved geometry that satisfied the optimal temperature and velocity distribution (heat distribution) inside the baking oven as a way to minimise the differences in the bread baked and maximise the energy utilisation from wood combustion. The CFD code Fluent on ANSYS 15 Workbench was used for numerical simulation.

This simulated case had several changes compared to the original design:

1) Diameter of the grid chimney reduced to 6 cm. A smaller diameter of the grid chimney means that less of the hot gas will escape and thus provide more heat into the oven.

2) Reducing 13 cm of the height of the baking oven. A lower height of the baking oven creates a more uniform flow pattern and increased heat transfer.

3) Decreasing 5 cm of the location height of the oven chimneys. The change of location of the oven chimneys is made to get a more uniform flow pattern.

RESULTS AND DISCUSSION

4. RESULTS AND DISCUSSION

4.1. Characteristics of bakery ovens

The bread baking process, wood usage, and combustion efficiency are important aspects of the WFBO. The pre-audit showed that 135 bakeries were located in the Maputo and Matola Townships and that the most common technologies employed to bake bread were indirect and semi-direct furnaces (Table 8). A total of 126 of these bakeries were validated: 96 were in Maputo, of which 33 used indirect and 37 semi-direct ovens, and 37 were in Matola, of which 19 used indirect and 15 semi-direct ovens. A total of 22 bakeries used natural gas or electricity as the source of heat: 19 in Maputo and 3 in Matola. Bakeries using natural gas or electricity are uncommon mainly due to high investment and running costs.

Table 8: Pre-audit results obtained in the Maputo and Matola Townships

Township	Nº of bakeries polled		Nº of valid replies	Type of oven		
	Operational	Closed		Indirect	Semi-direct	Other
Maputo	96	27	89	33	37	19
Matola	39	12	37	19	15	3
Total	**135**	39	126	**52**	**52**	22

The results of the questionnaire conducted during the pre-audit indicated that 1,902 bags of wheat flour (50 kg each), corresponding to 884,000 loaves, are processed in the two townships every day. In the Maputo Township, 816 bags of wheat (corresponding to 379,000 loaves) are processed in indirect ovens and 372 bags (corresponding to 173,000 loaves) in semi-direct ovens. In the Matola Township, 599 bags, (corresponding to 279,000 loaves) are processed in indirect ovens and 115 bags, (corresponding to 53,000 loaves) in semi-direct bakery ovens.

According to the pre-audit, the total amount of wood consumed by bakeries alone in both of the townships was around 60 tonnes per day, (Figure 4.1.1). Normally, this is green wood. In

Maputo, 41 tonnes are consumed: 25 tonnes in indirect furnaces and 16 tonnes in semi-direct. In Matola, 19 tonnes are consumed: 14 tonnes in indirect furnaces and 5 tonnes in semi-direct.

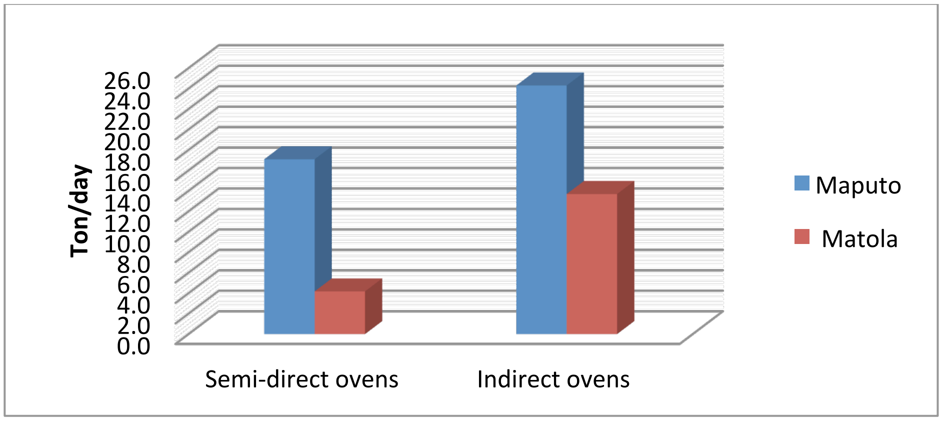


Figure 4.1.1: The amount of wood used daily in bread baking process in the townships of Maputo and Matola.

Although the characteristics of indirect and semi-direct bakery ovens are described in Paper I, it should nevertheless be noted that one of the main differences between them is that indirect ovens require electricity. The temperature profile of the baking process measured on the shelves of an indirect bakery oven remains constant at about 230±10ºC. Its efficiency, calculated in terms of SC, averages 0.55 kg of wood/kg of wheat flour baked. Despite a high degree of efficiency, the pre-audit revealed that this type of oven is not largely used in Mozambique due to the absence of electricity (and especially so in the countryside). It is moreover associated with high investment costs, which also includes installation and running costs.

A detailed audit was performed for 15 semi-direct bakery furnaces. The geometry and dimensions vary; this is mainly due to the furnaces being constructed with a high degree of empiricism, in that they depend on the experience of the constructor. The geometry of the combustion chamber, for example, can be either rectangular or round in shape. Measurements made in semi-direct bakery furnaces revealed that standard dimensions include a baking chamber having a diameter of 3 m. However, they varied between 2.6 and 3.55 m in diameter with standard deviation of 0.23.

The hot gases entering the baking chamber are either sucked through the combustion chimney located above the inlet fire-grate or through the baking chimney located at the centre of the baking chamber. Circulation of these hot gases within the baking oven implies an efficient heat exchange with the products being baked. The technical design is shown in Figure 1.2 as well as in Figures 1 and 2 in Appendix I. The natural and uncontrolled combustion with excess air, $\lambda = 3\pm1$ is predominant in this kind of bakery furnaces.

Bread is baked in batches. The number of bread baked is dependent on the dimension of the oven and is between 230 and 425 loaves for a single batch. Each bread weighs around 200 to

250 g. The feeding door is opened three times during the baking cycle, corresponding to more than 1/3 of the baking time. The circulation of heat within the baking oven is disturbed at the moment of opening, which was verified by the CFD model in Paper II. This affects the baking temperature negatively. The detailed audit showed that the efficiency in terms of SC is 0.90 kg of wood/kg of wheat flour baked with a standard deviation of 0.55, confirming that a large amount of wood is consumed in the baking process.

Characteristics of the wood burnt in the WFBO

Characteristics of the wood burnt in the semi-direct bakery furnace are described in detail in Paper III. The properties used to analyse the combustion of wood can be divided into four groups: physical, thermal, chemical and mineral (Ragland *et al.,* 1991). Thermal degradation products of wood consist of moisture, volatiles, char and ash. Some properties vary with species, position within the tree and growth conditions, while others depend on the combustion environment. The specific characteristics of the wood species used are shown in Table 9.

Table 9: Characteristics of the wood burnt in the WFBOs

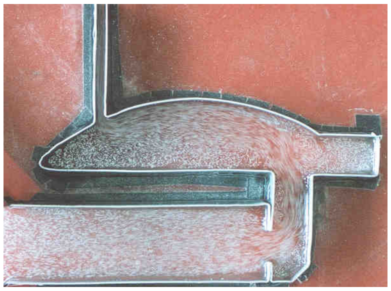
Vernacular Name	***Scientific Name***	***Density as received (kg/m3)***	***Moisture as received (%)***	***Ash as received (%)***	***HHV (kJ/kg)***
White Mikaya (1)	Acaceas	886.98	35.21	0.56	20.38
Xihoho (2)	Unknown	862.99	25.99	1.91	18.78
Mbeswu (3)	Albizia Versicolour	717.98	22.37	1.22	19.19
Nala (4)	Moprus Sp	1002.70	19.79	0.63	20.28
Red Mikaya (5)	Acaceas Sp	1172.46	16.32	2.4	19.58

The wood species were analysed to determine their influence on the combustion process. The density represents the amount of wood material available in a certain volume during the combustion process; the moisture gives the amount of energy that will be spent in evaporating the water that is present before the combustion process starts; the heat value represents the energy that can be released per unit mass when the fuel reacts completely with oxygen. From visual observations of the flame (a yellow flame is the result of uncompleted combustion and blue flame indicates a near complete combustion), good performance in the combustion process is achieved with wood that has low moisture content and high heat value. In this respect, specie 4 is considered as being very good. The ash that is formed around the wood in a WFBO tends to hinder the interaction between the air and the wood surface in the combustion process and thereby reduces the vivacity of the flame. Species 2, 3 and 5 showed such an ash layer resulting from combustion that impeded the process. To sustain the combustion process, this ash layer must be removed mechanically or the combustion rate must be increased by a higher intake of air. However, the latter alternative results in excess air, which decreases the temperature in the oven (Manhica *et al.,* 2012b). From the characteristic of the flame it appears that specie 5 is the most suitable for use in a WFBO. Its high density seems to prolong the combustion process, so the heat is released more uniformly compared to the other species used. This characteristic allows for stable temperatures in the whole baking process.

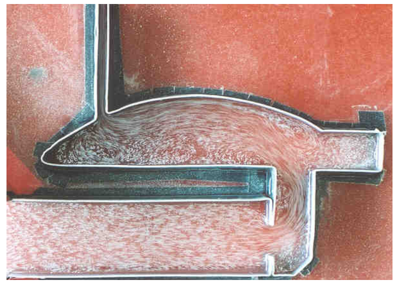
4.2. Air Flow

Radial and axial pressure gradients are formed in the baking oven due to the incoming gases (mainly air) from the combustion chamber. In case of a strong swirl, the adverse axial pressure gradient is sufficiently large to create an internal recirculation zone along the oven's axis and simultaneously reduce the outer recirculation zone near the wall. The baking quality is thereby affected; the uniformity of the product is affected negatively due to the non-uniformity of the air flow passing around it during the baking process (Manhica *et al.,* 2012b). A velocity increase of the air flow results in a larger weight loss, lower softness and darker surface of the bread. Therefore, either the baking time or temperature should be reduced to compensate for the increased heat transfer (Therdthai and Zhou, 2003). Carvalho and Nogueira (1997) showed how the air flow velocity in an oven chamber influenced the heat flux to the bread, as well as how the heat flux could be optimised. There is lack of data available on the aerodynamics of flow fields in bakery ovens. Especially for wood-fired bakery ovens that utilise natural air draughts in the combustion chamber. In many cases, experimental work lacks accuracy due to difficulties in conducting measurements.

A mathematical model (Paper II) was used to interpret variations in the inlet velocities of hot gases coming from the combustion chamber. Figure 4.2.1 shows the flow patterns of both the bi-dimensional cold flow model and the mathematical modelling. The upper row in the figure shows the differences in the flow with an inlet velocity of 0.015 m/s, 0.030 m/s and 0.0375 m/s, respectively, and the lower row shows the contours of the stream lines at inlet air velocities of between 0.3 m/s and 0.74 m/s, which corresponds to the same Re number as in the cold flow experiments.

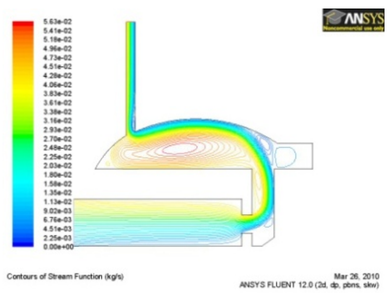


Water velocity = 0.015 m/s at 300K

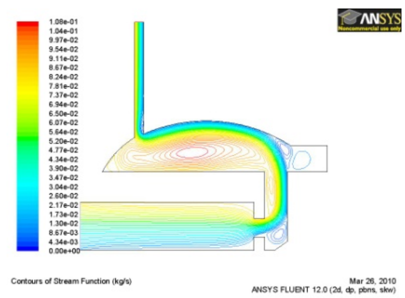


Water velocity = 0.030 m/s at 300K

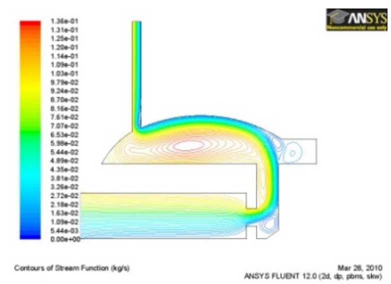
Water velocity = 0.0375 m/s at 300K



Contours of stream lines at 0.3 m/s and 1500K



Contours of stream lines at 0.59 m/s and 1500K



Contours of stream lines at 0.74 m/s and 1500K

Figure 4.2.1: Comparisons of the velocities field flows in the 2D cold flow and mathematical models.

This flow pattern can be used to predict the conditions that will be produced in the oven. In this context, the analysis is based on the relationship between the vortices created by the flow and the heat exchange. The dynamic vortex that appears inside the baking oven varies with the velocity of the inlet air and determines the convective heat exchange between the dough and the hot air as a correlation of the Nusselt number and the absolute vortices flux (TorII and Yanagihara, 1989 and Momayez *et al., 2004)*.

When wood is consumed at a rate of 18 kg/h, the lowest velocity of the inlet air (valid for λ=2) in the cold flow model, i.e. 0.015 m/s, corresponds to 0.30 m/s in the mathematical model. It shows that the flow pattern is characterised by a uniform flow: from the grid inlet to the baking oven and then to the chimney, with only little formation of vortices. This characteristic is typical of poor heat transfer expressed in terms of effective thermal conductivity: 0.863 W/mK between the gases and the imagined dough (placed on the floor of the baking oven). An increase in the velocity (λ=4) corresponding to 0.59 m/s in the mathematical model implies that the gases can be circulated to a higher degree, without changing the flow pattern inside the baking oven, as shown in Figure 4.6. At the highest velocity, i.e. 0.74 m/s in the mathematical model (equals λ>4), the effective thermal conductivity is increased to 3.07 W/mK. In this stage, there is excessive heat inside the baking oven that affects the quality of the bread (Manhiça *et al.,* 2009). At the lowest velocity magnitude (0.3 m/s), the maximum quantity of hot gases circulating in the bakery oven is 0.0056 kg/s; this increases with increasing velocity magnitude to a value of 0.011 kg/s at 0.59 m/s and 0.136 kg/s at 0.74 m/s.

The experimental measurement of the air flow rate to the combustion chamber of a WFBO is shown in Paper III. The measurement revealed that the inlet velocity varied significantly, and that the variation occurred within a matter of seconds, Figure 4.2.2.

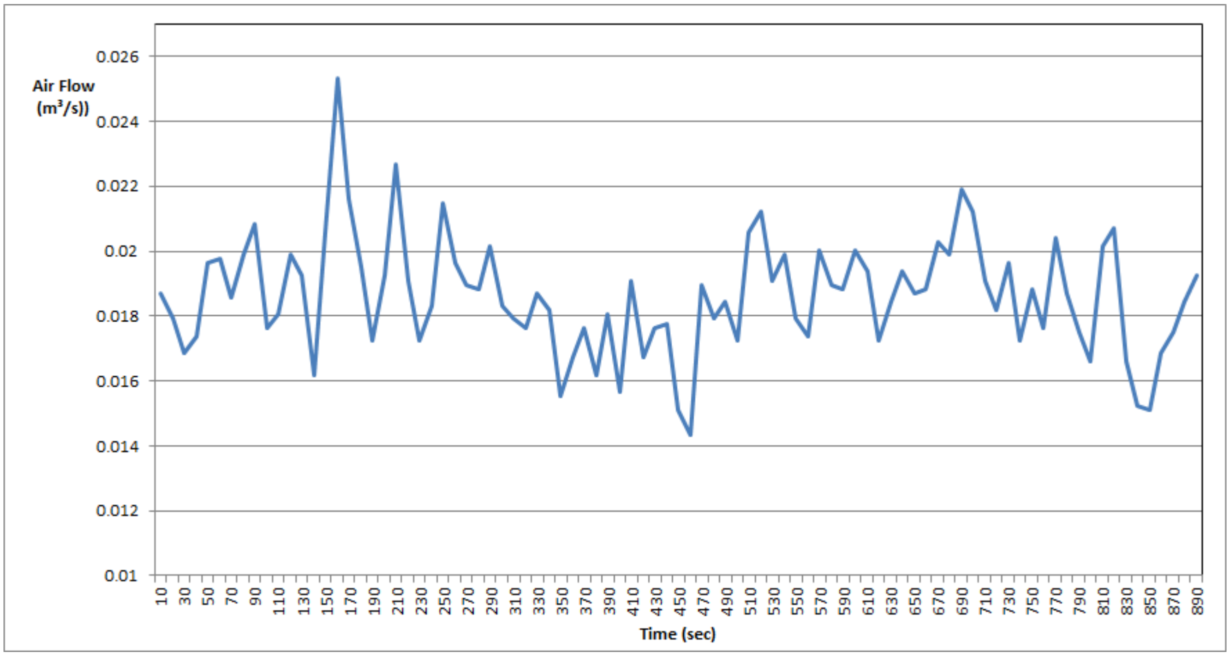


Figure 4.2.2. Variation of the rate of the air flow in the combustion chamber of a WFBO.

Physical and 2D Mathematical Models

Qualitative analysis of the flow patterns in the bi-dimensional water simulation was used to improve the geometry (i.e. shape) of the oven. Even with dimensional differences, the qualitative results clarify the differences in circulation of the gases from the combustion to the baking chamber. It is clear that the geometry influences the flow pattern inside the bakery furnace. In bakeries with a rectangular-shaped combustion chamber, it is evident that the dead zones influence the heat and mass transfer between the baked product and the hot gases negatively. The flow pattern of the gases in the round design is suitable but still not the most optimum alternative (Appendix II, Figures 3 and 4).

4.3. Temperature Profile

Temperature profile from detailed audit (Paper I)

Temperature is the main factor for the physico-chemical changes that occur during the baking process. The operating conditions in the baking oven need to be optimised to reduce the consumption of fuel and to achieve a high quality of the product. The common industrial practice employed to achieve optimal baking is to ensure constant temperature within the baking oven. Predicting the baking performance of wheat dough is difficult, as mechanisms of baking are not fully understood (Mondal and Datta 2008). Temperature measurements made in different parts of a wood-fired bakery oven showed that the temperature is stabilised along the main duct that leads to the grid. This stabilisation in temperature does not occur inside the baking chamber; where the variation in temperature in the combustion (grid) chimney is at its greatest (350±50ºC), and can be compared to the temperature of 200±30ºC in the oven chimney, see Figures 4.3.1 and 4.3.2. The variation in temperature is caused mainly by the feeding door to the baking oven being opened, as well as by natural convection of the air flowing into the combustion chamber.

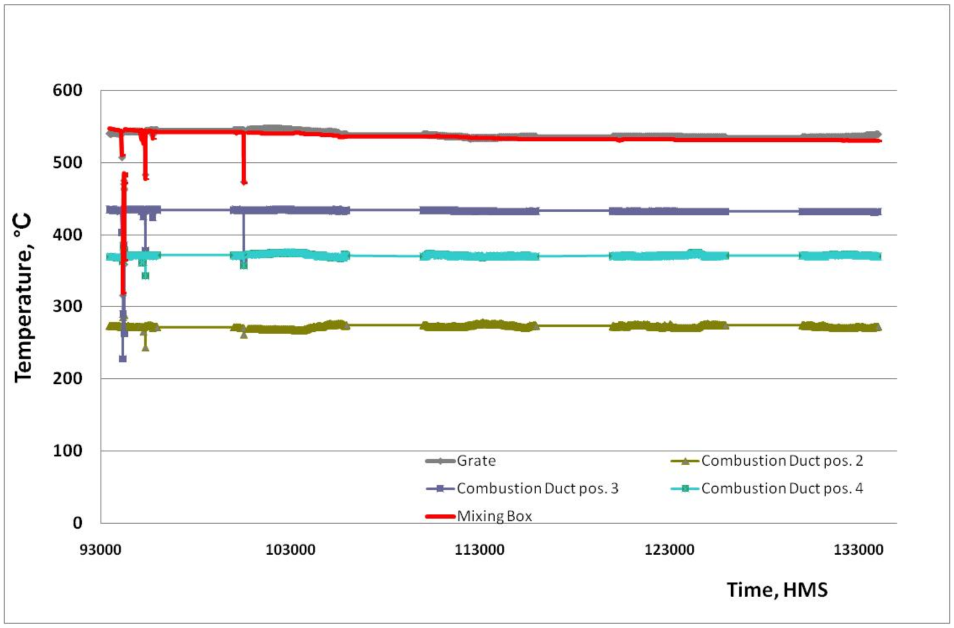


Figure 4.3.1: Graph of the temperature profile in the combustion chamber.

Figure 4.3.2: Graph of the temperature profile in the chimneys.

Opening the feeding door affects the flow of combustion gases in the baking oven and in the chimneys. This phenomenon, which is studied in detail in Paper II, greatly affects the temperature profile of the baking process and thereby the baking time, with direct consequences for the bread quality. Although the static pressure within the oven is only slightly less than that of the surroundings, it is sufficient enough to draw air via the feeding door into the interior of the baking oven. Two phenomena occur as a consequence of this: some of the surrounding air is carried into the oven and some of the hot gases escape from the oven due to their high velocity. Consequently, some WFBOs have a collector for hot gases (i.e. a chimney) placed directly above the feeding door to prevent hot gases from entering into the work place. This provides better working conditions for the bakery operator when both placing dough in the oven and removing the bread from it. However, the efficiency of such a baking process is less than that of a process with a closed feeding door. Figure 4.3.3 compares the flow patterns of ovens with an open and a closed feeding door at the same inlet velocity (0.59 m/s), with respect to (a) velocity, (b) turbulent energy, (c) effective thermal conductivity and (d) dynamic pressure. The magnitude of these parameters decreases when the feeding door is opened.

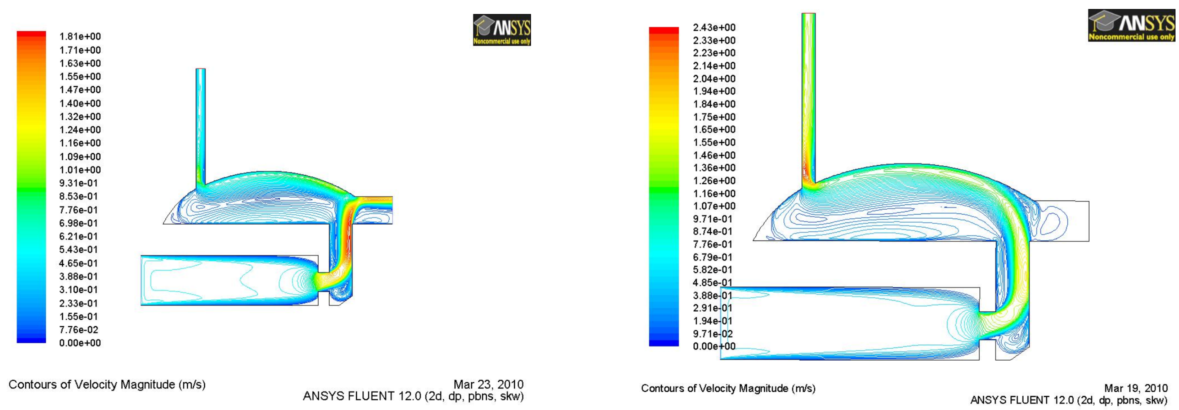


Figure 4.3.3: a) Velocity, flow patterns in a WFBO when the feeding door is opened (left) and closed (right).

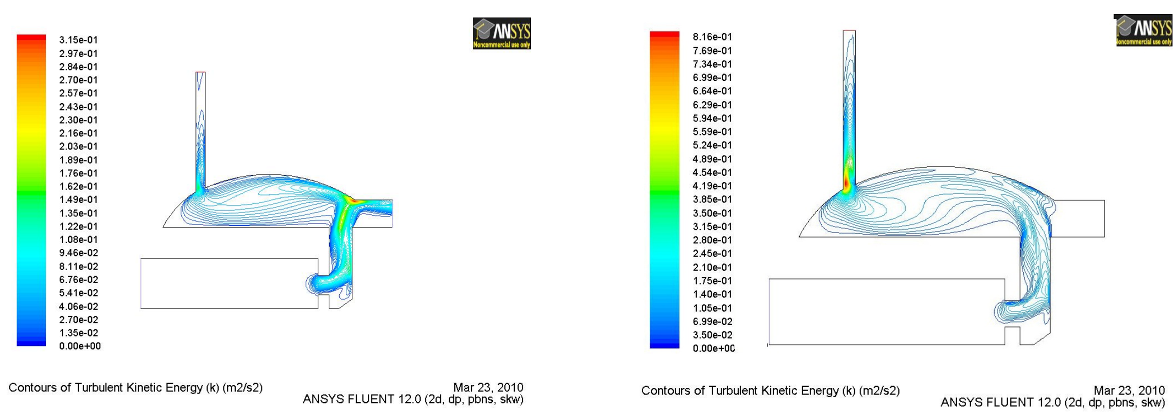


Figure 4.3.3: b) turbulent energy, Flow patterns in a WFBO when the feeding door is opened (left) and closed (right).

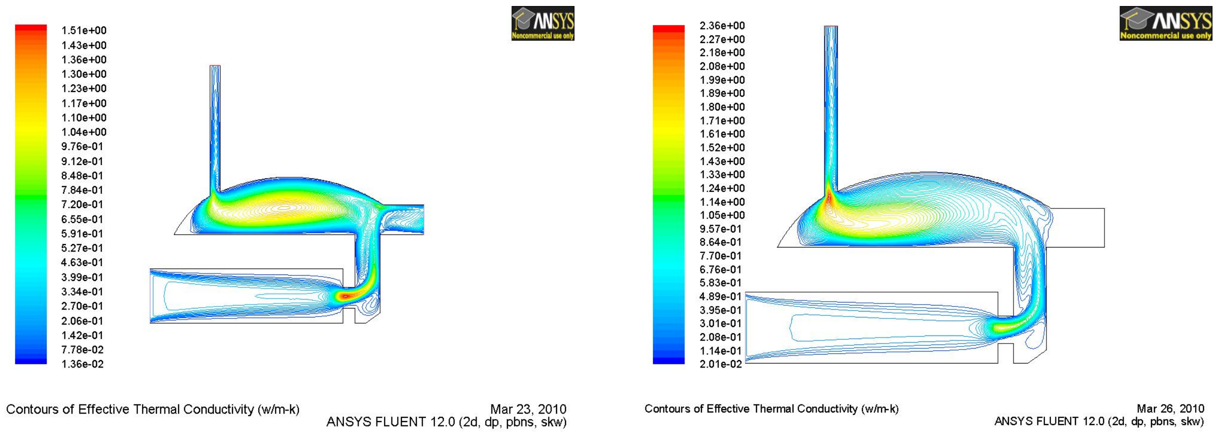


Figure 4.3.3: c) effective thermal conductivity, Flow patterns in a WFBO when the feeding door is opened (Left) and closed (right).

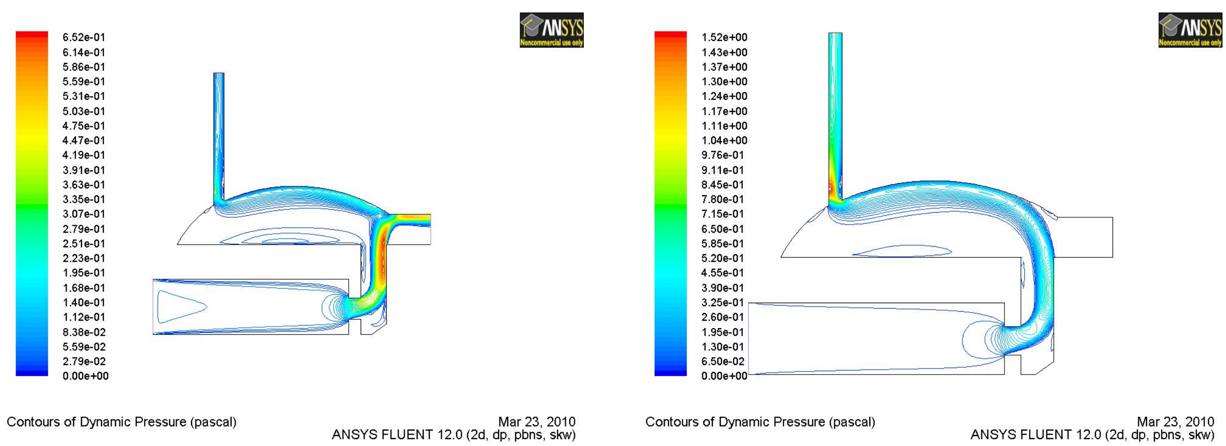


Figure 4.3.3: d) dynamic pressure, Flow patterns in a WFBO when the feeding door is opened (left) and closed (right)

The effects caused by opening the feeding door are inherent in the baking process, which occurs manually and in batches. This phenomenon significantly affects the temperature profile of the baking process and the baking time. In addition, the variations in the flow of air from the inlet to the combustion chamber also affect the hot gases that proceed to the baking oven. Opening the feeding door allows some of the surrounding air to enter the baking oven and, simultaneously, hot gases to exit from its top edge and thereby enter the working environment. The CFD model presented in Paper II describes the influence of the air flow from the combustion chamber on the temperature profile inside the baking oven, and Paper III shows the experimental procedure to estimate the air flow to inlet of the combustion chamber of the WFBO.

Temperature Profile in the Mathematical Model

The combustion of wood, the design of the furnace, the composition of the fuel, the way in which the fire is tendered and the rate at which fuel is fed into it are the most important parameters determining the thermodynamic efficiency of a WFBO. Other parameters include the design of the baking chamber, the baking practice employed and meteorological conditions.

Poor control of the inlet air contributes to inefficient combustion; resulting negative effects arise when the excess air is beyond the typical range ($2 \leq \lambda \leq 4$) (Luca and Blasiak, 2000). Incomplete combustion occurs below this range and, if the flow of inlet air is too high, the temperature will be too low. This, in turn, could give slow reaction rates and thereby result in incomplete combustion. However, even within the range of excess air, the temperature distribution and turbulent kinetic energy inside the oven are strongly influenced by the velocity of the inlet air. At low inlet velocities (0.3 m/s), the temperature is low (745K) at the fire-grate inlet of the baking oven, and the circulation of the hot gases will be weak inside the oven. An increase in velocity enhances many of the parameters that are important for baking. The temperature is the dominating factor regarding the quality of the product during the baking process, since it affects the enzymatic reactions, volume expansion, gelatinisation, browning reaction and migration of water. The pressure gradient, induced by water evaporation and migration, causes swelling of the bread (Therdithai *et al.*, 2003). Figure 4.3.4 shows correlations of the inlet velocity with minimum and maximum temperatures, turbulent kinetic energy and effective thermal conductivity. An increase in velocity gives more turbulent kinetic energy, higher effective thermal conductivity and higher temperatures in the oven.

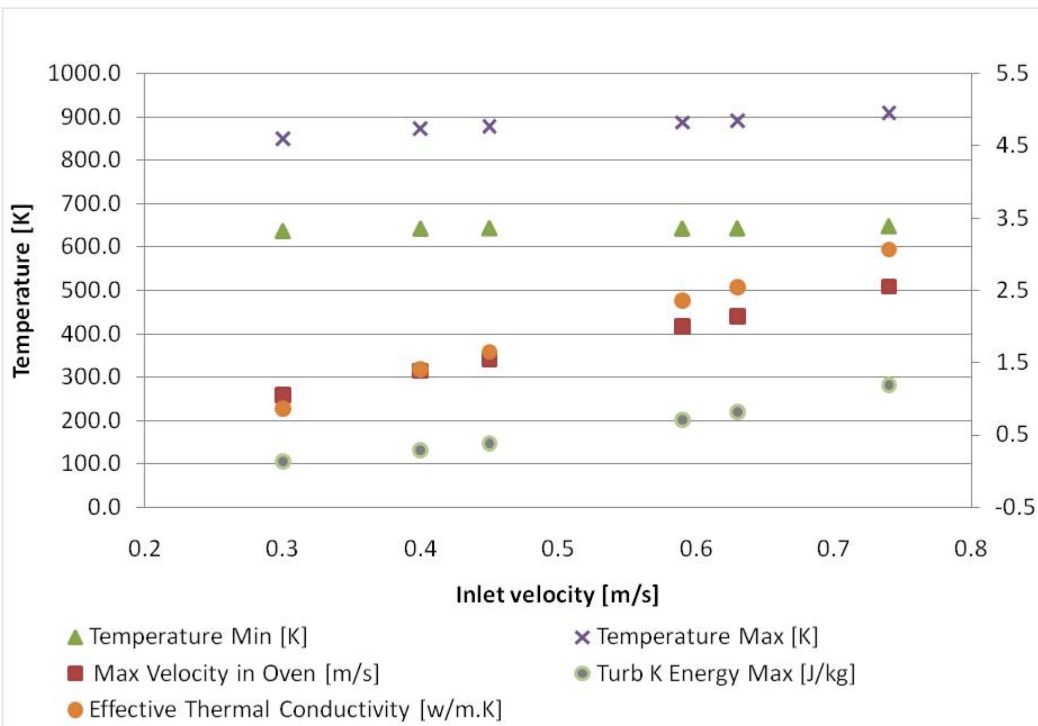


Figure 4.3.4: The impact of velocity on several parameters (Temperature at left Y Axis and other parameters at right Y Axis)

In the range of complete combustion, as shown in Figure 4.3.5 b), atmospheric conditions may vary in such a manner that the velocity of the inlet air entering the combustion chamber increases. This might result in an increase in temperature and faster recirculation of the hot gases inside the baking oven, as well as an increase in the wood consumption. The recirculation of gases due to the turbulent kinetic energy enhances the degree of heat exchange between the gases and the products, determined as the effective thermal conductivity of the gases. It should be noted that the main flow pattern inside a WFBO is almost the same, regardless of the velocity of the inlet air within this range. This means that variations in the velocity of the inlet air mainly affect the amount of heat transferred to the dough by convection and the amount of hot gases that circulate inside the baking oven; as mentioned above, they will directly influence the quality of the bread produced.

a) b)

Figure 4.3.5: Various stages in the combustion of logs in a WFBO.

The desired temperature, achieved from measurements in different wood-fired bakery ovens, was found to be in the range of 700–800 K at the inlet fire-grate in order to achieve an end product of good quality (Manhica *et al.,* 2012a).

Temperature Profile In WFBO (Paper III)

The typical temperature profile in the WFBO during a 24 hour period is shown in Figure 4.3.6 a); the temperature profile that corresponds to the production time is magnified in Figure 4.9b). Figure 4.3.6 a) is subdivided into 3 parts. Parts I and III correspond to the night shift, when wood is burnt only to maintain the temperature inside the WFBO; the amount of wood used during night shifts averages 79 kg/night. Part II corresponds with the production period; it shows the production profile during the day shift, when the temperature must be increased to bake the bread. Bread was produced for a period of only 4 to 6 hours a day when the measurements were taken, which differs significantly from a full commercial WFBO that produces day and night. If only the production period is taken into consideration, the results show that an average of 0.61 kg of wood/kg bread baked was consumed, which can be compared to the typical value of 0.90 kg of wood/kg of bread baked (Manhica *et al.,* 2012a) a)

b)

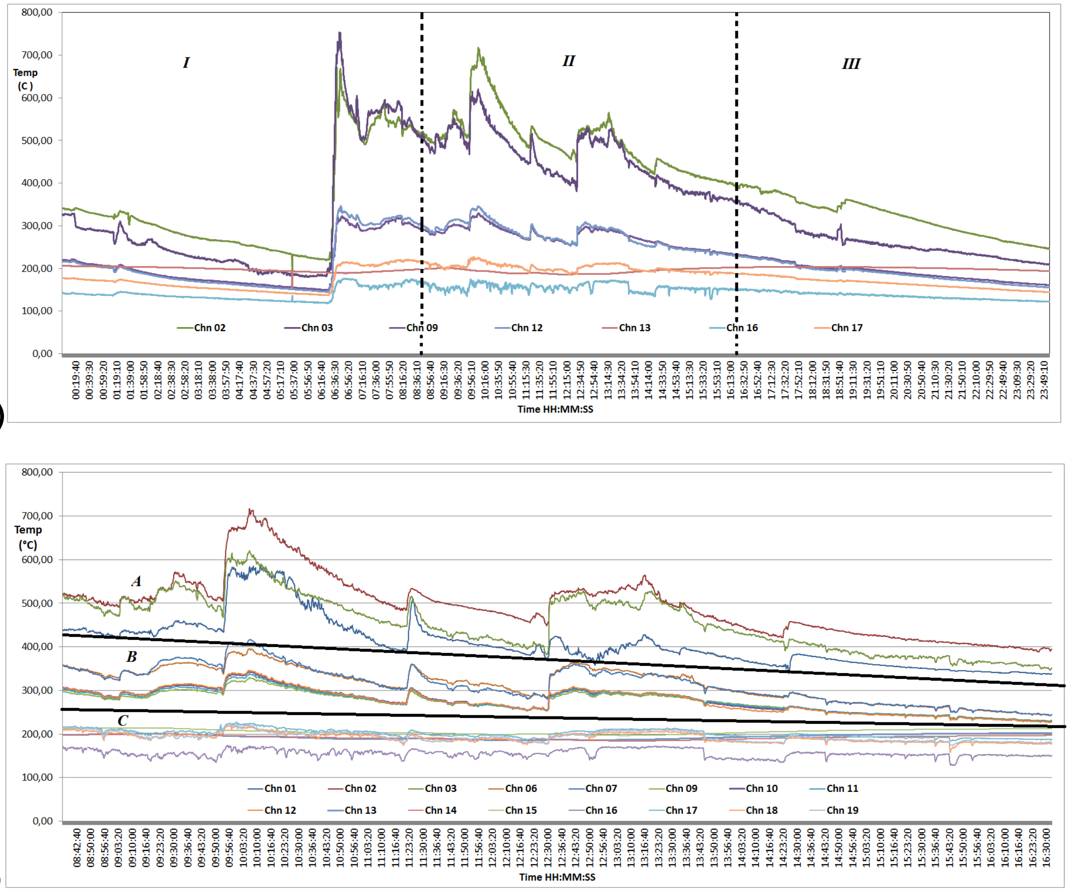


Figure 4.3.6: A typical temperature profile in a WFB, where a) is for the whole 24 hour period and b) is for the actual production period.

In Figure 4.3.6b, zone A represents the temperature profile in the combustion chamber, zone B the temperature profile in the main duct and grid and zone C the temperature profile in the oven and chimneys. In general terms, the temperature profile in a WFBO is characterised by large fluctuations in zones A and B, which are the consequence of variations in the inlet air flow to the combustion chamber, as well as smooth fluctuations from the grid to the chimneys (zone C).

The ceiling temperature in a WFBO is between 230 and 250°C whereas the floor temperature is constantly around 210°C. During the production period, the temperature of the gases that escape via the oven chimney (point 16 in Figure 3.4.2B) is lower (≈140 to 190°C), represented by the bottom line on Figure 4.3.6b than the gases that escape via the grid chimney (point 17 in Figure 3.4.2B) (≈180 to 230°C)

The high circulation of heat close to the ceiling of the oven compared to that of the floor was investigated experimentally. This supports the theory that radiation is an important mode of heat transfer in the baking process (Carvalho and Nogueira, 1997) based on the fact that the ceiling absorbed most of the heat from the grid. The measurements taken in this investigation along the height of the oven confirm this statement. Figure 4.3.7 shows the temperature measured from various points in the oven. The green line represents the measurements taken using the thermocouple in position 20, the brown line those taken with the thermocouple in position 19 and the blue line those taken with the thermocouple in position 18 in the Figure 2.4.2B.

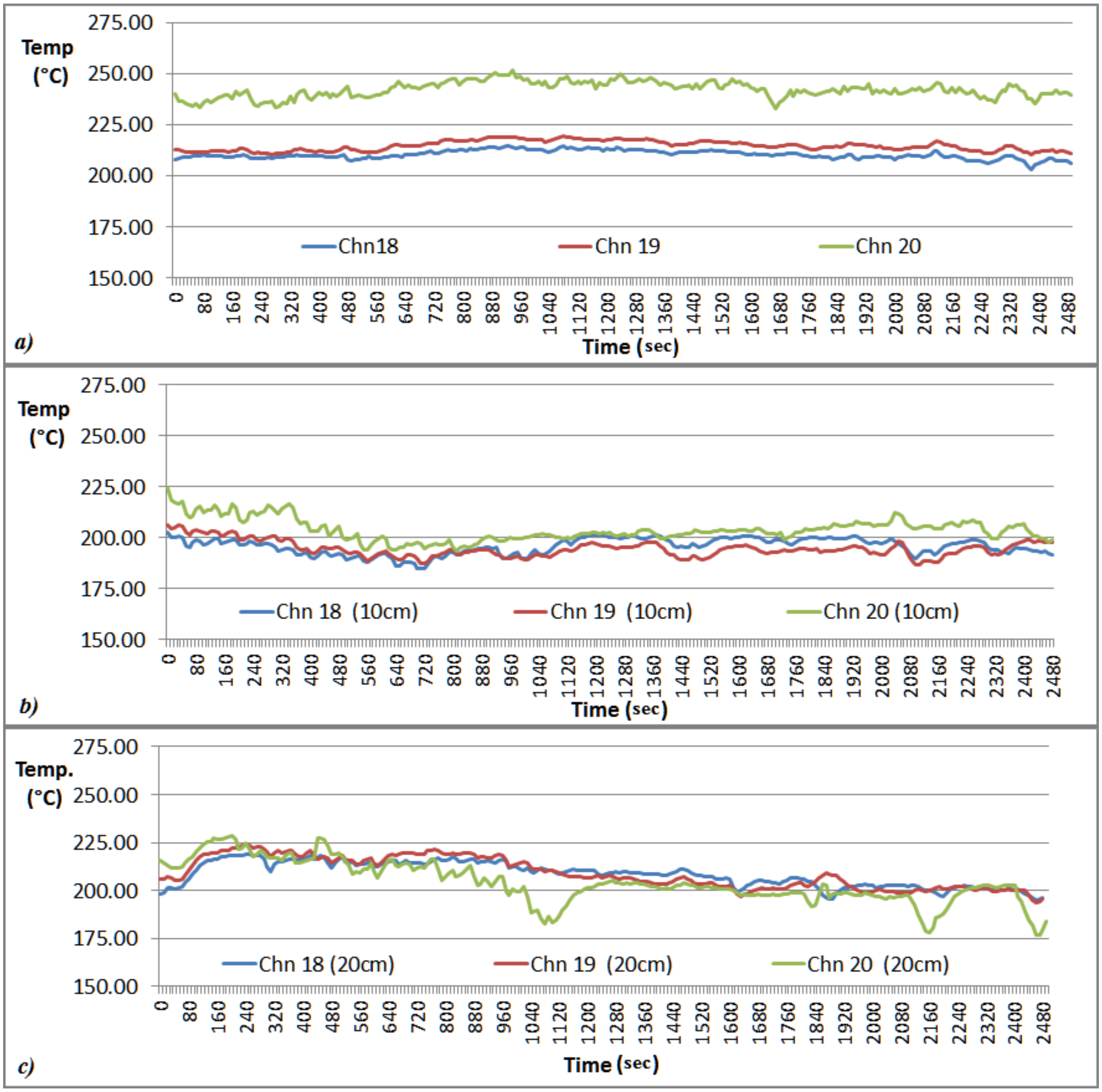


Figure 4.3.7: *Temperature profiles at different distances from the ceiling of the baking oven during the baking process.*

a) Normal measurement position of the thermocouple in the ceiling; b) 10 cm below the normal measurement position; c) 20 cm below the normal measurement position.

The measurements indicate that the hot gases lose part of their energy to the ceiling. The contact between the hot gases and the bread dough must be improved if the efficiency of the oven is to be increased. This could be made possible by reducing the height in the baking oven so that the vortex formed has full contact with the dough.

4. 4. Bread Quality

Temperature profile inside the dough and its impact on the final product

The first index of quality of soft baked products is the temperature measured in the centre (Thorvaldsson and Skjoldebrand 1998). It is here where the gelatinisation of starch occurs and is characterised by a harmonic increase (Zanoni *et al.,* 1995a). The surface temperature was assumed to approach the oven temperature when the feeding door is kept closed, a situation that rarely occurs, Figure 4.12A. The surface temperature is more or less always affected by the feeding door when it is opened.

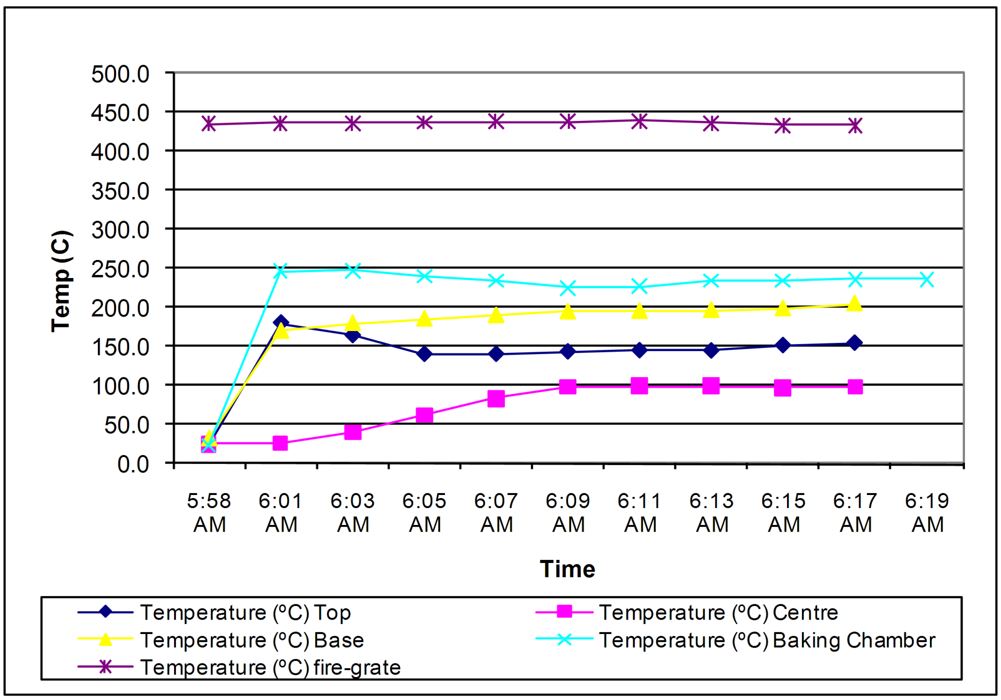
Heat is transferred from the outer layer of the loaf to its centre during baking. Whilst the temperature increases quickly at the surface, it increases much more slowly in the centre, Figures 4.4.1A and 4.4.1B. Consequently, the partial pressure of the water vapour at the surface is higher than in the centre; in an attempt to reduce the pressure difference, water vapour migrates towards the centre. However, the temperature in the centre of the loaf is lower than at its surface, so water vapour condenses. The internal temperature in the centre then increases, keeping it constant at a maximum of 100ºC. The temperature in the crumb is normally stable during the last baking stage. Figures 4.4.1A and 4.4.1B illustrate that the baking chamber directly influences the speed at which the temperature profile changes in the crumb. When the temperature is high (i.e. 450ºC at the fire-grate inlet), the temperature of the crumb increases more rapidly than when it is low (i.e. 350ºC at the fire-grate inlet). In the former case, the temperature of the crumb reaches a value close to 100ºC in 12 minutes (centre temperature); in the latter, it takes 16 minutes. The temperature in the baking chamber also has a direct influence on the crust and bottom of the loaf; the temperature at the bottom of the loaf is higher when the fire-grate temperature is at 450ºC than at 350ºC. However, temperature measurements of the bread surface temperature are difficult and several cases must be considered:

I. Case I The thermocouple is on the surface of the dough all the time. It follows the movement of expansion in its volume exactly.
II. Case II The thermocouple is on the surface initially. It later sinks due to expansion in the volume of the dough.
III. Case III The thermocouple is above the surface of the dough in order to measure the baking temperature only.

An increase in temperature of 60ºC in the first stage enhances enzymatic activity and yeast growth, resulting in an increase in the volume of the crumb; an increase that is in the order of one-third of the original volume. Furthermore, the surface skin loses elasticity, thickens and starts to take on a brown appearance.

Figure 4.4.1A illustrates Case II, in which the thermocouple sinks with time, thus measuring the temperature a few millimetres below the crust. It can be seen that, at fire-grate temperature

450ºC, the top temperature drops in the first 6 minutes but rises again in an attempt to reach the baking temperature. This temperature will not, however, be reached; the loaves are kept cool by evaporation and this stage is completed before all of the water has been evaporated. In the later stages of baking, the surface temperature of the end product enhances the flavour, according to the Maillard reaction associated with browning and this gives a darker crust. The Maillard reaction requires reduced sugars and amino-compounds as reactants. The temperature of the crumb never exceeds the boiling point of water (100°C). However, the temperature of the crust eventually reaches above 200°C when the oven temperature remains at a constant temperature of 220–240°C. For this reason, heat transmission during baking favours the formation of Maillard reaction products (melanoidins) in the bread crust. Figure 4.4.1B shows Case I with a fire-grate temperature of 350ºC where it can be seen that the top temperature is lower than the temperature in the baking chamber during almost the whole baking process and as a consequence, the baking time is increased.



A

B

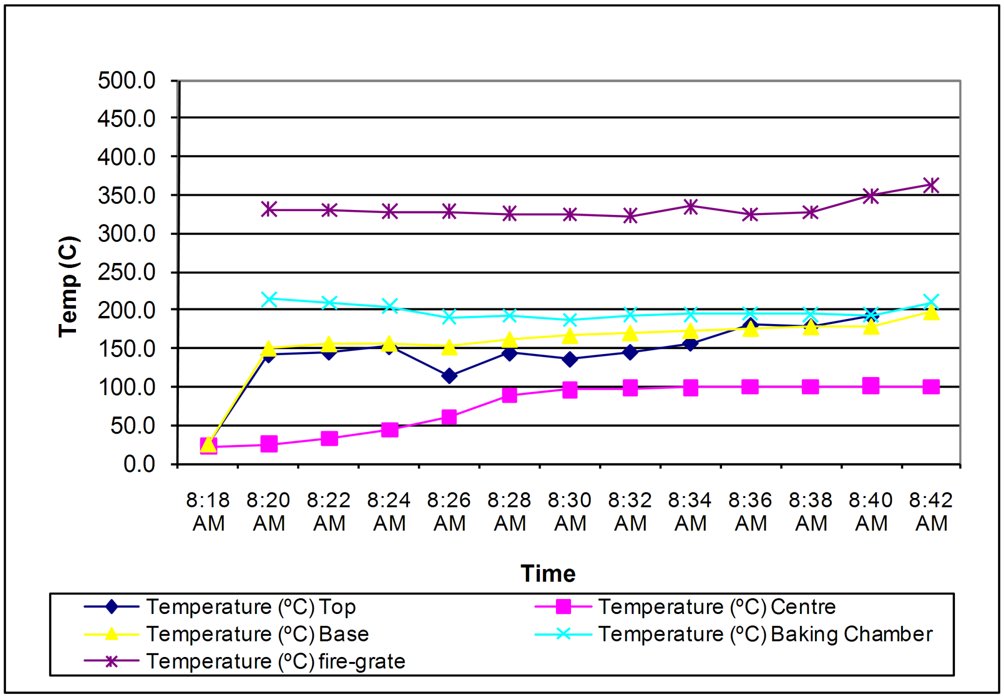
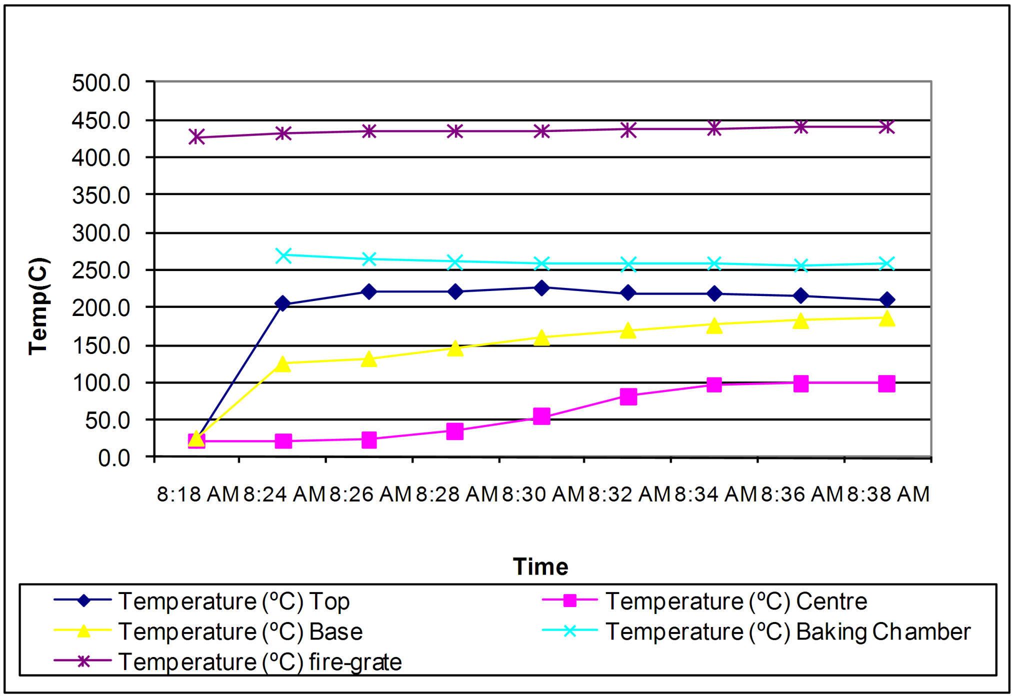
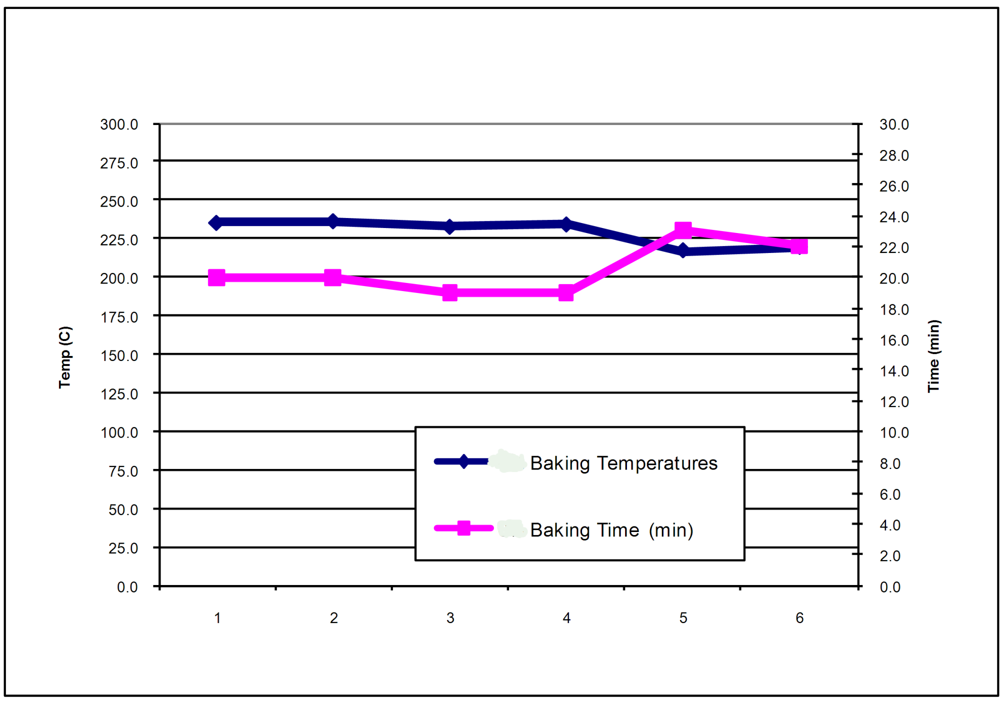


Figure 4.4.1. A. The temperature profiles measured in a loaf of bread baked at the fire-grate temperature 450°C. B. Temperature profiles measured in a loaf of bread baked at fire-grate temperature 350°C.

During the crust formation process, it is necessary to achieve the right amount of vapour in the oven. A low amount of steam results in a thinner crust, which has a high vapour transmission rate and permeability. It is expected that such a crust will remain crisp for longer time during storage (Altamirano-Fortoul *et al.,* 2012). However, increasing crust water vapour permeability may give an increased water loss from the inner crumb, which would lead to unwanted crumb dryness (Hirte *et al.,* 2012). A typical temperature profile for the baking process is illustrated in Figure 4.4.2A for Case III: the temperature at the top of the loaf reaches the baking temperature in both cases, i.e. 450ºC and 350ºC in fire-grate temperature. The baking time in one and the same bakery oven is dependent on the baking temperature: a high baking temperature results in a short baking time, fine crust formed and low moisture content in final product; however, when the temperature is low, it results in long baking time, thick crust formed and high moisture content in the bread. This relationship is illustrated in Figure 4.4.2B.



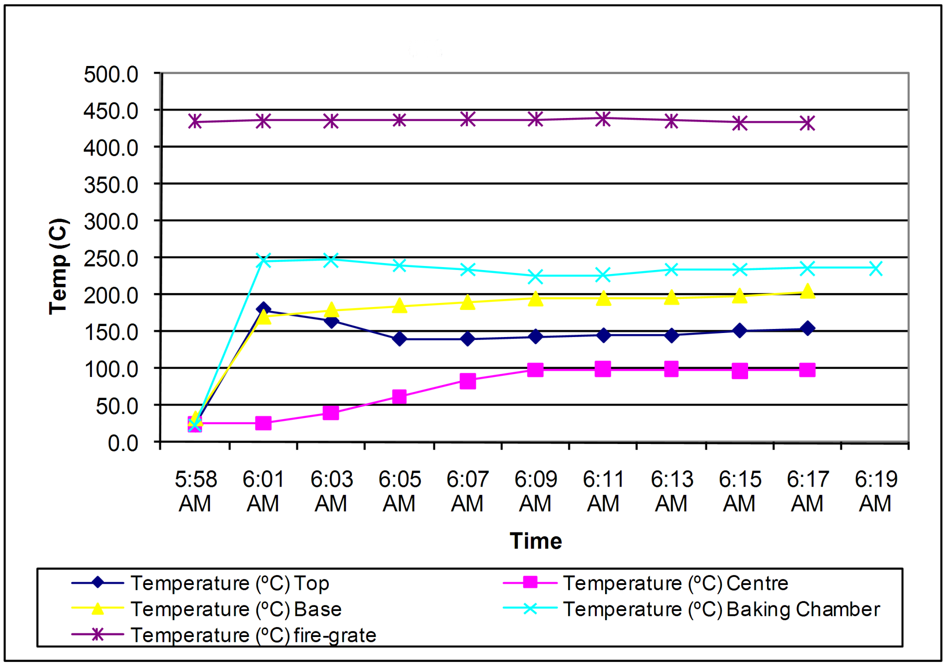
A



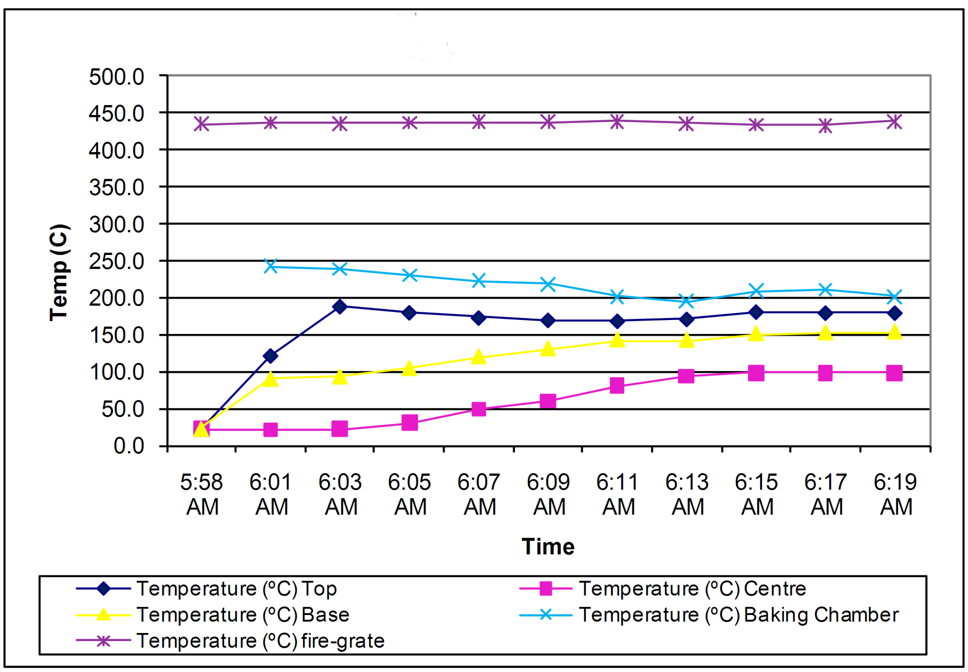
B

Figure 4.4.2. A. The temperature profile of bread baked when the feeding door is kept closed. B. The relationship between baking time and temperature in the baking oven.

Bakery products are also judged by their final colour, which is a result of reactions that occur during baking as a result of heat. Temperature and water gradients rise during the baking process and, as a consequence, the properties of texture and colour depend on the position in the oven. Figures 4.4.3A and 4.4.3B show the temperature profiles measured at positions P1 and P2 (see Figure 3.1.B). It can be seen that the distribution of the temperature is not homogeneous. A numbers of factors have been suggested to explain these differences. Among those are: baking geometry, effect of opening the feeding door, location of the combustion chimneys and variations in the air flow.



A



B

Figure 4.4.3. A. Temperature profile measured at position P2 in a semi-direct WFBO when the bread is baked at the fire-grate temperature 450°C. B. Temperature profile measured at position P1 in a semi-direct WFBO when the bread is baked at the fire-grate temperature 350°C.

The experimental data shown in Table 10 confirms that the baking time follows the baking temperature, and that both parameters influence the colour of the crust. The colour of the crust is an important attribute of bread, contributing to consumer preference. The crust acts as a barrier, thereby preventing the loss of water and flavour during baking (Zanoni *et al.,* 1995b). The colour develops as a function of the moisture content, baking time and baking temperature (Zanoni *et al.,* 1995c). The shelf life of a baked product is affected by the time and temperature of the baking process (Mondal and Datta 2008). Thermal preservation process and the inactivation of pathogenic and spoilage microorganisms and enzymes require a minimal treatment temperature and corresponding holding time (Jaeger *et al.,* 2010). Whilst a long baking time due to low baking temperature increased the L values (the colour intensity) to 72.40, the colour of the top crust and the average colour of the crust were both too pale. A short baking time due to high baking temperature lowered the L values to 54.33, resulting in the crust being significantly darker. The temperature at the top of the loaf remains below 150ºC for a long period of time when the fire-grate temperature is 350ºC, which is not conducive for the Maillard reaction to occur. It can be seen in Figure 4B that the temperature at the top of the loaf became higher than 150ºC after 14 to 16 minutes, with the result that the total baking time was as long as 24 min.

Table 10: The analysed parameters of the baked bread in wood-fired bakery oven.

Parameters	**Fire-grate temp. 450ºC**	**Fire-grate temp. 350ºC**
Water activity, a_w	0.60 to 0.92	0.73 to 0.95
Baking time (min)	18 ± 2	24 ± 2
Moisture content (g)	36.5	39.5
Colour (L)	54.3	72.4
Shelf-life (day)	4	3

Water molecules play a complex role in bread products at every stage, from the preparation of the dough to the moment of consumption, and especially so during the relatively brief period of processing at elevated temperature. The water activity is defined as the current volume and availability of "free" water in a sample and should not be directly compared with water content (g water/g substance). It ranges between 0 (absolute dryness) and 1 (condensed humidity) and is responsible for the microbiological growth on surfaces, which influences the microbiological stability. The migration and equilibrium properties of water in food are an important point for the shelf life stability, and the water activity can thus be used as an indicator for the microbial stability of combined bakery products. A high baking temperature is necessary to achieve an optimal level of the water activity in the products. Water activity for these baked breads varies in the range of 0.60 to 0.92 using a fire-grate temperature of 450ºC, and in the range of 0.73 to 0.95 for a fire-grate temperature of 350ºC. The low temperature during the baking process contributes to an increase of the water activity, which reduces the shelf life of the baked bread. Table 11 shows that mould appeared on the bread baked at a fire-grate temperature of 350ºC, on the third day of its shelf-life. The general quality attributes, i.e. average water activity and moisture content, of bread baked in wood-fired bakery ovens are illustrated in Figure 4.4.4.

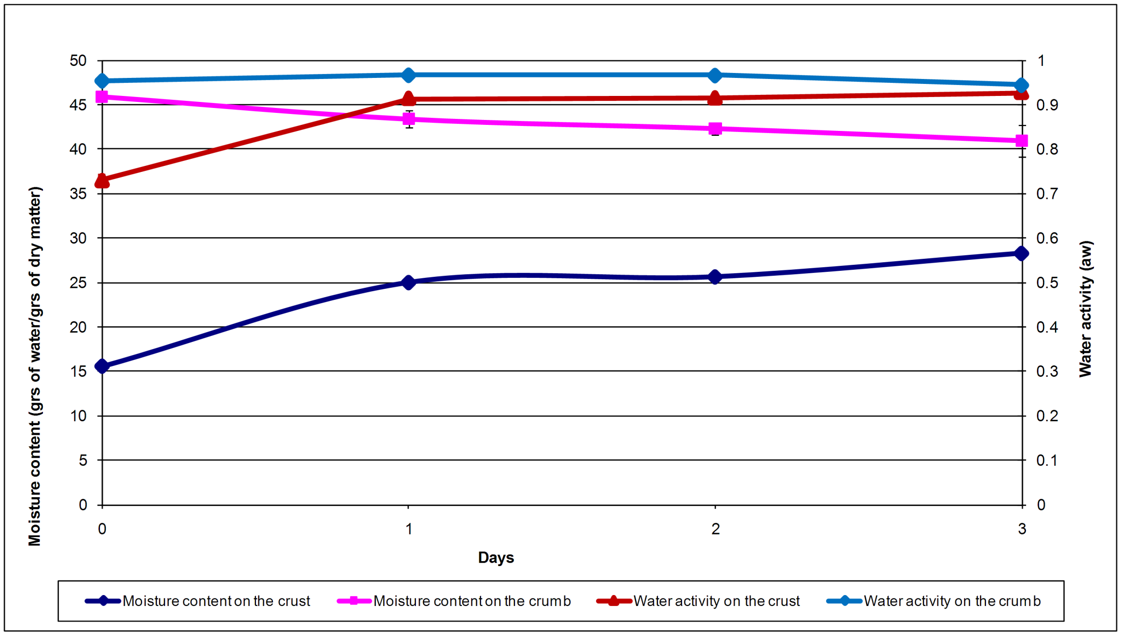


Figure 4.4.4. Moisture content and water activity of the bread analysed.

More specifically, water activity and colour of the bread sample baked in the WFBO shown in Figure 3.4.4 were studied in Paper III. These parameters also relate to the baking process such as colour, moisture content and ash in both crust and crumb.

The temperature profile on the floor of the baking oven shows that the temperature is higher at points 13 and 15 than at point 14 (Figure 3.4.2B), which can be explained by the effect of conduction. More heat is transferred from the ceiling of the combustion chamber than from the parts around the base of the oven, which is further explained in Paper IV.

Another parameter that influences the baking process is the baking time, which is generally defined as the time from when the first loaf of bread is placed in the oven until the last loaf in the same batch has been removed. As a consequence, loaves of bread in the same batch have varying qualities due to the differences in the time exposed to the heat. Table 11 shows the differences in colour, water activity and moisture content in the crumb and crust of the loaves of bread baked in the same batch. The loaf of bread in position 1 (Figure 3.4.4) has much longer baking time compared with all of the other loaves in the same batch: it not only has the best properties in terms of colour (dark) and moisture content (7.40 crust and 38.24 crumb) but relatively low levels of water activity in both the crust and crumb (0.456 and 0.996). The loaves in positions 5 and 6 had less baking time in the oven compared to the loaf in position 1, but all have approximately the same characteristics as far as quality parameters are concerned due to the additional heat transferred by conduction.

Loaves produced in positions 2 and 4 show high values of water activity and moisture content in the crumb and crust, and they are paler in colour. This is due to a too short baking time with respect to the present heat flux.

The bread baked in different batches with different species of the wood fuel, have different qualities. In case of low heat intensity in the oven, the baking time is increased to maintain the quality of the bread. This increased baking time reduces the number of the batches that can be produced and thus reduced the production rate.

Table 11. Properties of bread baked in one batch in a WFBO.

Properties		Bread in Pos. 1				Bread in Pos. 2				Bread in Pos. 3			
		Crust	*STDEV*	*Crumb*	*STDVE*	*Crust*	*STDVE*	*Crumb*	*STDVE*	*Crust*	*STDVE*	*Crumb*	*STDVE*
Water Activity		0.456	*0.013*	0.996	*0.004*	0.539	*0.005*	0.999	*0.001*	0.488	*0.005*	0.998	*0.001*
Colour	L	42.93	*0.300*	55.61	*0.389*	52.11	*1.47*	58.74	*2.6*	47.22	*0.412*	59.49	*0.275*
	a	20.34	*0.245*	6.37	*0.18*	19.41	*0.68*	6.59	*0.083*	18.68	*0.045*	6.50	*0.070*
	b	32.21	*0.232*	22.40	*0.83*	37.71	*0.172*	22.27	*0.175*	34.39	*0.247*	22.51	*0.192*
Moisture Content (%)		7.4	*0.131*	38.24	*0.31*	11.48	*0.47*	41.34	*1.22*	8.91	*0.04*	40.40	*0.31*

Properties		Bread in Pos. 4				Bread in Pos. 5				Bread in Pos. 6			
		Crust	*STDVE*	*Crumb*	*STDVE*	*Crust*	*STDVE*	*Crumb*	*STDVE*	*Crust*	*STDVE*	*Crumb*	*STDVE*
Water Activity		0.491	*0.003*	0.993	*0.000*	0.499	*0.007*	0.998	*0.000*	0.533	*0.015*	0.998	*0.001*
Colour	L	50.92	*0.292*	57.4	*0.351*	41.51	*0.483*	59.71	*0.44*	44.60	*0.303*	58.49	*0.185*
	a	17.68	*0.273*	6.39	*0.32*	19.63	*0.46*	6.47	*0.37*	19.70	*0.199*	6.81	*0.230*
	b	36.44	*1.05*	22.47	*0.55*	31.82	*0.348*	22.92	*0.95*	34.14	*0.226*	23.18	*0.800*
Moisture Content (%)		8.92	*0.20*	40.61	*0.22*	7.40	*0.061*	38.89	*0.31*	8.45	*0.16*	39.35	*0.25*

Shelf life

Shelf life is another method used to evaluate bread quality (Paper III). The shelf life of a baked product is affected by the time and temperature of the baking process (Mondal and Datta 2008). According to Jaeger *et al.* 2010, the preservation process and the inactivation of pathogenic and the spoilage of microorganisms and enzymes require a treatment temperature and corresponding holding time. Table 12 shows that mould appears first in the loaves of bread with levels of high water activity (baked in positions 2, 3 and 4). These results are in accordance with the effects of the heat distribution and the baking times during the baking time as shown by (Manhica *et al.,* 2012a and Jaeger *et al.,* 2010 a).

Table 12: The appearance of mould in bread baked in different positions.

Samples	Qualitative evaluation (%)				
	Day 1 (% of mould)	Day 2 (% of mould)	Day 3 (% of mould)	Day 4 (% of mould)	Day 5 (% of mould)
Bread 1	0	0	0	20 to 30	100
Bread 2	0	0	30	100	
Bread 3	0	0	20	80 to 90	100
Bread 4	0	0	30	100	
Bread 5	0	0	0	20 to 30	100
Bread 6	0	0	0	20 to 30	100

4.5. Oven Geometry and Heat Transfer Process (3D Mathematical Model)

Temperature and velocity distribution (flow pattern)

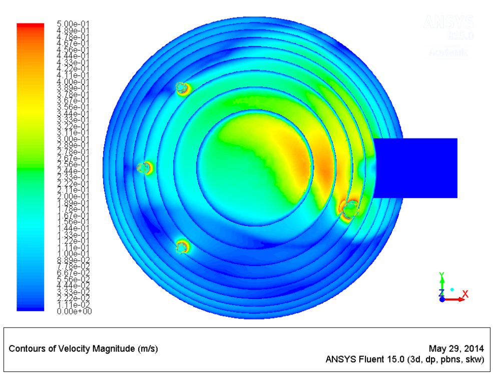
The heat transfer mode, velocity and temperature distribution in the oven were analysed to find out which factors influence the bread baking process. The maximum velocity in the bakery oven was found in the duct region (3.7 m/s). The velocity at the grid outlet is down to 0.5 m/s due to the increase in the cross-section area. The mass flow rates and heat flux at different positions in the oven are presented in Table 13.

Table 13. The mass flow rate and heat flux measured in the WFBO used.

	Mass flow rate (kg/s)	***Heat Flux (kW)***
Inlet + Wood Source	*0.0196*	*14.12*
Outlet Chimney 1	*0.00344*	*0.44*
Outlet Chimney 2	*0.00318*	*0.46*
Outlet Chimney 3	*0.00313*	*0.56*
Outlet Grid Chimney	*0.00984*	*1.92*
Average at the Breads	-------	*0.35*
External Losses	-------	*10.39*

The majority of the hot gases (50%) that cross the grid outlet escape through the grid chimney. The remaining hot gases are distributed between the areas in which chimneys 1, 2 and 3 are found. This distribution creates low velocity zones (0.016–0.32 m/s) in the remaining parts. The velocity of the hot gases is close to zero at the surface of the oven base; the increase in the viscosity coefficient tends to reduce the velocity of the flow of fluids to zero at the walls. Figures 4.15a and 4.5.1b represent the velocity and temperature profiles, respectively, in the whole oven. Regions of low temperatures are noticeable in the baking oven and they coincide with regions where the velocity magnitude is low.

a)



b)

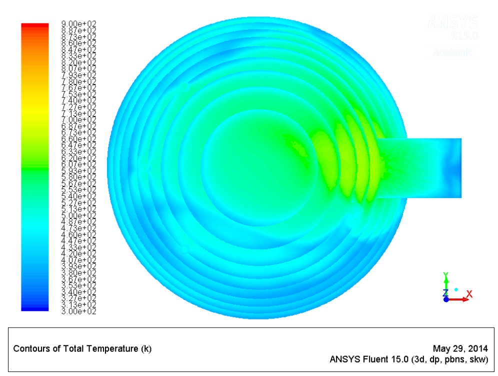
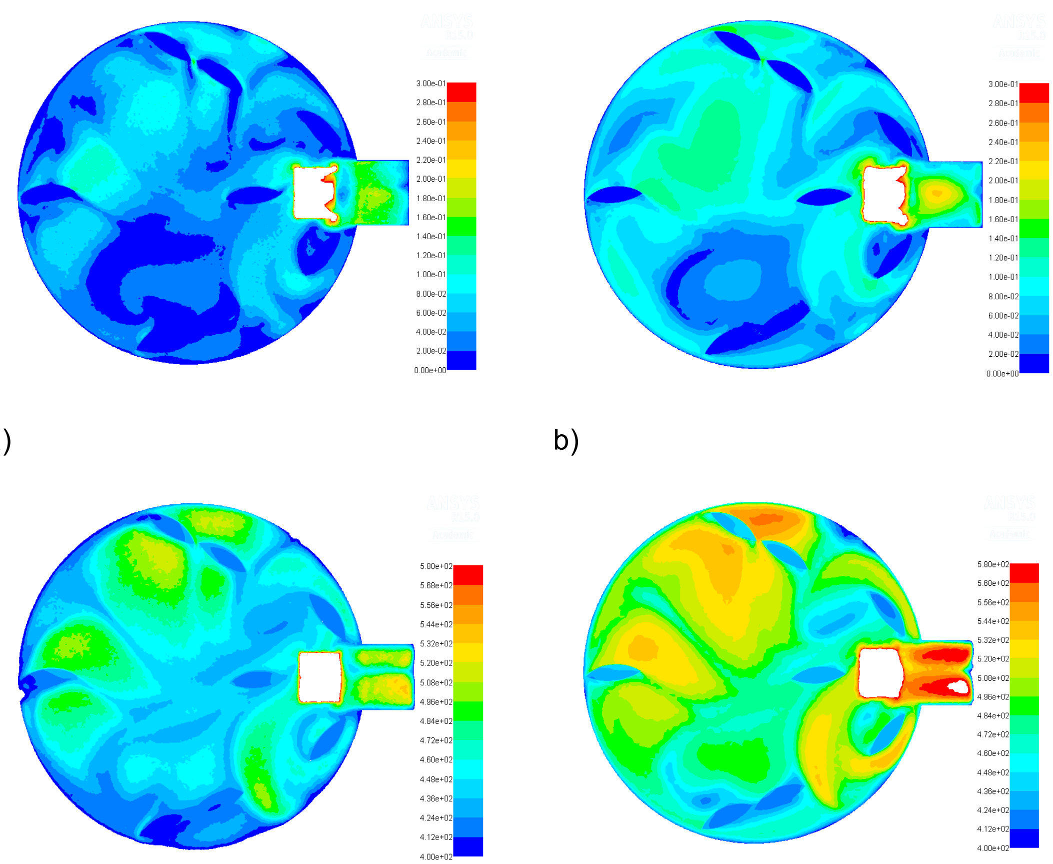


Figure 4.5.1: Velocity (a) and (b) temperature profiles in entire baking oven.

A comparison of the flow pattern of the current model results with previous 2D model (Manhica *et al.,* 2012b) can be done by taking a longitudinal cut at the central section of the WFBO. It shows very good agreement and verifies the conclusion previously drawn regarding e.g. the existence of a vortex in the oven. The newly made 3D model gives additional spatial information. The results of the mathematical model concerning previously recorded temperature measurements (Manhica *et al.,* 2013) show accurate agreement.

Heat transfer and its effect on the baking process

Baking a whole batch of bread with uniform quality is achieved by a combination of baking time and overall heat transfer in the oven. The distribution of heat in the oven is strongly dependent on the flow patterns, which, to a large extent, are dependent on the geometry of the oven. The temperature and the velocity of the hot gases in the oven influence the heat transfer mode in the baking process. A low velocity, with a corresponding low temperature, of the gases gives a low convection heat transfer, so radiation is often the predominant mode of heat transfer during the baking process (Carvalho and Nogueira, 1997 and Velthusis *et al*., 1993). However, in regions where the velocity of the hot gases is high, heat transfer by convection is more effective (Khatir *et al.,* 2012). The discussion regarding the heat transfer process is, for clarity, divided into the three modes: conduction, convection and radiation. Figure 4.5.2 shows the velocity and temperature profiles of Model 2 (baking oven with bread). The height of the surface of the bread is 5 cm above the base.



a) b)

c) d)

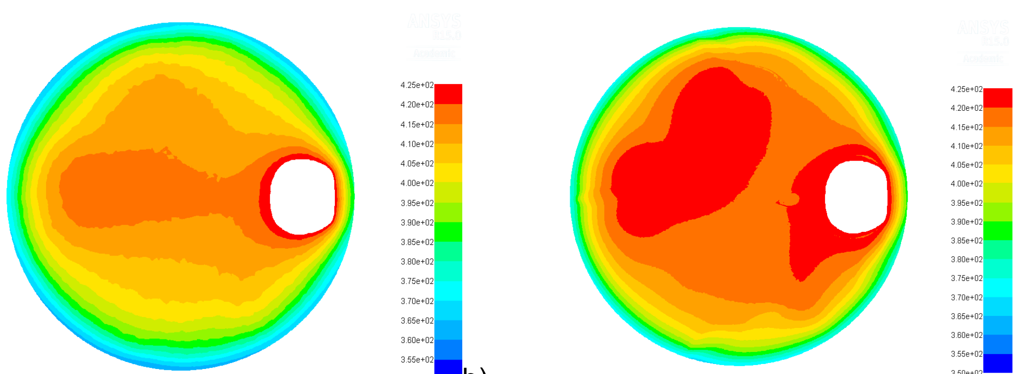
Figure 4.5.2: Velocity and temperature profiles in the baking oven containing bread. Velocity profile at a height above the oven base of a) 1 cm and b) 5 cm. Temperature profile at a height above the oven base of c) 1 cm and d) 5 cm.

The results of both models show that the temperature and velocity vary with height in the baking oven: both are high for hot gases close to the top wall of the oven and are lowest close to the base.

Conduction

The combustion of wood in the combustion chamber of a WFBO occurs at temperatures in the range of 800–1200 K. Such high temperatures affect the walls, which then increase in temperature. On top of the combustion chamber are four different layers. First, a layer of bricks, then a layer of sand, which is followed by a layer of salt and a final layer of bricks. The sand layer (≈15 cm) is used as insulation material to prevent the temperatures from becoming too high at the base of the oven. The salt, with a thickness of around 5–10 cm, is used as a buffer layer for storing heat between the combustion chamber and the baking oven. The increment in temperature of the oven base is dependent on the temperature that develops on the combustion chamber but should never exceed the melting point of the salt (1074 K) at the position of the salt layer. The salt layer maintains the temperature of the oven base by absorbing heat during the melting process, if the temperature exceeds 1074 K and releasing it when the temperature is low.

Figure 4.5.3 a) shows the temperature profile in the salt layer (situated 1cm below the oven base) and illustrates the differences in conductive heat transfer to the oven base. The part of the oven base that is situated directly above the combustion chamber has significantly higher temperature compared to the rest of the oven base. The temperature at the base of the oven increases due to convection and radiation heat that is transferred from the top walls of the oven. Figure 4.5.3 b) shows the temperature distribution on the actual oven base surface when simulating an empty oven. This figure also includes convection and radiation in addition to the conduction.



a) b)

Figure 4.5.3: Temperature distribution in a WBFO a) in the salt layer and b) at the base of the oven.

Convection

The rate at which heat is transferred by convection to the bread's surface is related directly to the velocity and temperature of the gas as well as to the shape of the loaf of bread. The velocity is the result of the combustion process together with the design of the nozzle at the end of the combustion chamber (Manhica *et al.,* 2012b). The residence time of the hot gases is dependent on the geometry of the baking oven, the format of which means that two regions can be identified: (i) a zone where a large vortex is created by the movement of hot gases in the central region of the oven and (ii) several regions that are not affected significantly by the grid chimney. The irregular distribution of the hot gases in the oven creates dead zones where both velocity and temperature are low.

Radiation

Heat transferred by radiation is the result of energy transferred from the hot walls of the oven, and has almost the same effect in the whole oven. The hot gases that go along the top wall of the baking oven have a temperature of around 665 K. Figure 4.5.4 shows the temperature distribution along the oven ceiling.

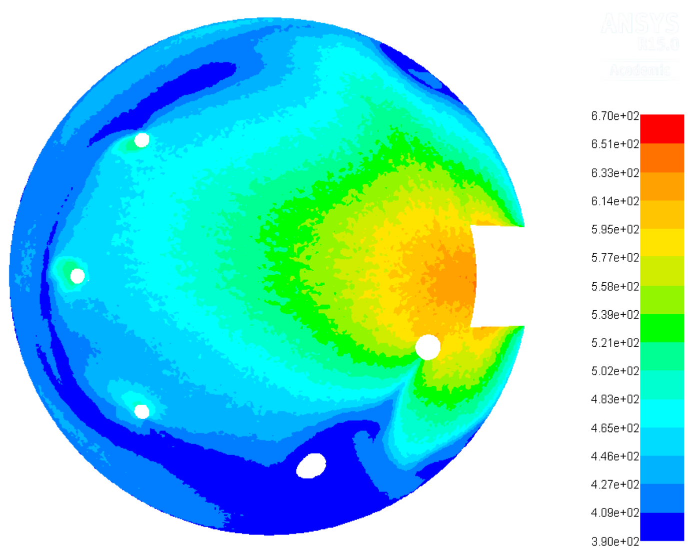


Figure 4.5.4: The temperature distribution along the oven ceiling

The bread baking process

A combination of heat transfer, flow pattern and baking time is used to explain the differences between the bread loaves baked in one batch. During the baking process, the temperatures in the different positions in the oven base influence the heat transferred by conduction. Table 14 reports the outer surface temperature of the bread samples at zero minutes, and at transient conditions in the WFBO. The transient results show the temperature at a specific time during the baking process.

In general, the contribution of the conduction and convection is high at the beginning compared to the end of the process. The heat flux is initially zero and reaches its maximum value during the baking process and decreases again at the end. The samples located directly above the top of the combustion chamber are more influenced by conduction than the other samples due to the higher temperature of the oven base in these positions. According to Figure 4.5.2b, which shows the assumed constant oven base temperatures, the samples located in positions 7 and 5 (see Figure 3.4.4) will have the highest heat transfer by conduction due to the higher temperature in these positions. However, the samples located in positions 3, 7 and 5 receive 441, 437 and 435 K, respectively, from heat transferred by convection and radiation, as shown in Table 14. After 20 minutes, samples 3 and 5 receive most heat by radiation and convection during the baking process, followed by 7, 2, 6 and 1; Samples 8 and 4 receive the least.

The loaves baked in the region with a low velocity and low temperature, as shown in Figures 4.17 a) and b), have the lowest temperatures (Samples 4 and 8) as well as the lowest average temperature. Sample 2 is located close to the grid outlet and therefore is part of the loaf subjected to high convection heat whilst the remainder is exposed to low convectional heat. The total amount of heat received is nevertheless high when compared with Samples 4 and 8.

Table 14: The temperatures of the bread samples.

<table>
<tr><th rowspan="4">Samples</th><th colspan="9">Flux (W)</th></tr>
<tr><th colspan="7">Transient</th><th colspan="2" rowspan="2">Infinite time
(Steady State)</th></tr>
<tr><th>0 min</th><th colspan="3">10 min</th><th colspan="3">20 min</th></tr>
<tr><th>Surface and Base temp (K)</th><th>Base Temp (K)</th><th>Surface Temp (K)</th><th>Total Heat Flux (W)</th><th>Base Temp (K)</th><th>Surfac e Temp (K)</th><th>Total Heat Flux (W)</th><th>Base Temp (K)</th><th>Surfac e Temp (K)</th></tr>
<tr><td>1</td><td>300</td><td>361</td><td>384</td><td>47.19</td><td>376</td><td>391</td><td>25.71</td><td>414</td><td>426</td></tr>
<tr><td>2</td><td>300</td><td>364</td><td>388</td><td>49.43</td><td>380</td><td>396</td><td>26.98</td><td>415</td><td>428</td></tr>
<tr><td>3</td><td>300</td><td>363</td><td>403</td><td>51.70</td><td>379</td><td>403</td><td>27.94</td><td>421</td><td>441</td></tr>
<tr><td>4</td><td>300</td><td>356</td><td>378</td><td>44.64</td><td>371</td><td>387</td><td>24.35</td><td>406</td><td>422</td></tr>
<tr><td>5</td><td>300</td><td>363</td><td>397</td><td>50.60</td><td>380</td><td>399</td><td>27.41</td><td>417</td><td>435</td></tr>
<tr><td>6</td><td>300</td><td>367</td><td>387</td><td>49.50</td><td>384</td><td>395</td><td>26.90</td><td>422</td><td>428</td></tr>
<tr><td>7</td><td>300</td><td>366</td><td>398</td><td>51.85</td><td>384</td><td>396</td><td>28.04</td><td>415</td><td>437</td></tr>
<tr><td>8</td><td>300</td><td>360</td><td>377</td><td>45.76</td><td>375</td><td>388</td><td>24.98</td><td>412</td><td>421</td></tr>
</table>

The model with breads provides details of the distribution of heat inside the oven during the baking process. Regardless of how the bread is fed into the baking oven, the loaves should have different baking times because the heat flux is not uniform throughout the oven. The irregular distribution of heat means that some loaves are baked faster than others in the same batch. Common practice is that loaves are fed into the oven one line at a time (Manhica *et al.,* 2012a), but normally they are all discharged at the same time (i.e. bread removal is much faster than bread loading). Samples 3 and 7, for example, reach 372 K (99°C) after 14 to 15 minutes. It will take samples 4 and 8 an additional 4 to 5 minutes to reach this temperature and if removed at the same time they will not be ready; thus, a trade-off with respect to baking time must be made to achieve high enough quality of the whole batch. The temperature profile and the difference in baking time in each sample baked in the same batch are illustrated in Figure 4.5.5.

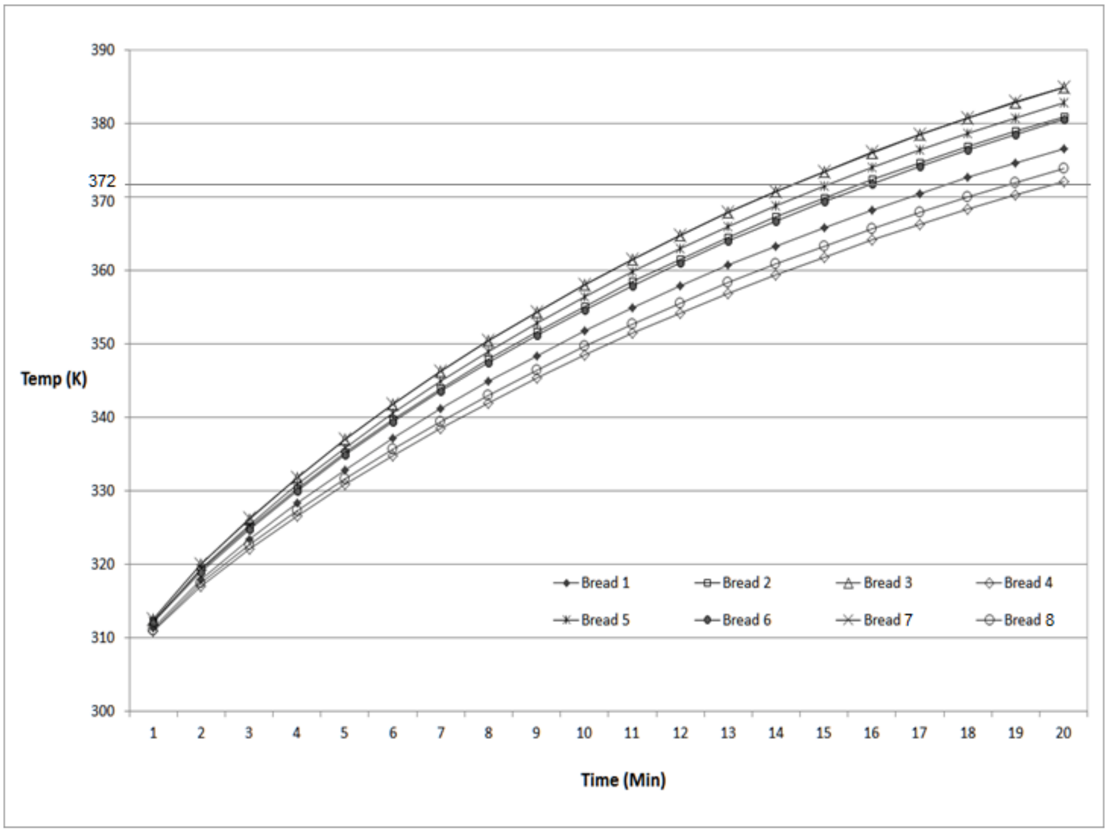


Figure 4.5.5: Average temperature profiles of the bread samples during the baking process. The line at 372 K corresponds to the required final bread temperature.

4.6. Optimization of the Oven Geometry

Previously a 3D CFD model (below considered as model 0) was created and experimentally validated by the temperature profile at the grid outlet (Manhica *et al.,* 2013). This model was then used to study the flow when geometrical changes were made of the baking oven in order to find a more even temperature and heat distribution. The changes in the flow effects: the residence time of gases, the magnitude of convection, conduction and radiation heat transfer and the baking time of each loaf during the baking process. The changes were compared with the original design of the WFBO to evaluate the improvements on new design.

Reduction of the grid chimney diameter is essentially equivalent to a reduction of the amount of gases that leave the oven before releasing their energy content. The reduction of hot gases through the grid chimney can also be made via a damp at the top of the chimney. The damp is constructed of a metal plate with a weight as a lever for automatic control of the opening depending on the pressure in the oven; low pressure keeps the damp closed and increased pressure will open the damp. The pressure inside the oven depends on the velocity of the inlet air flow and the surrounding atmospheric condition. This dependence makes it difficult to calculate the exact weight of the level. The velocity of the gases inside the oven is dependent on the total amount of gas present inside. When there is high amount of gases leaving through the grid chimney, the velocity of the gases in the oven will be lower. Table 15 summarises the differences of the mass flow and heat flux in the oven in the original and the modified geometry.

Based on the results, it can be suggested that the hot gases could be delayed to leave the oven by using the numerous holes along the chimney in such a way that the pressure becomes high close to the base of the chimney pipe. The problem in this method is how to calculate the number and diameter of the holes to get the adequate pressure magnitude in a situation of a natural draught.

Table 15. The mass flow rate and heat flux measured in the original and the modified geometry.

	Original Geometry		Modified geometry	
	Mass flow rate (kg/s)	Heat Flux (KW)	Mass flow (kg/s)	Heat Flux (KW)
Inlet + Wood source	0.0196	14.12	0.0196	14.12
Chimney 1	0.0034	1.92	0.0049	1.20
Chimney 21	0.0032	0.44	0.0049	1.66
Chimney 3	0.0031	0.46	0.0049	1.68
Grid Chimney	0.0098	0.56	0.0049	1.22
Bread average		0.35		0.41
External losses		10.39		7.95

The change of the grid chimney diameter makes the mass flow in the modified geometry balanced on all chimneys and thus distributes the gas flow around in the whole oven.

The magnitude of convection, conduction and radiation heat transfer was determined by the final temperature at the surfaces and bases of the bread and top wall of the oven at steady state condition and at the end of the baking process simulation. The results of the baking time of each sample in the original geometry together with the result from the geometry modification in the oven are shown in Table 16. The baking time in this study is defined as the time to reach 372 K (99°C).

When a fluid flows over a bread surface, the first layer of the fluid sticks to the boundary and this causes the flow to retard. From the original geometry, it was concluded that there is a central vortex that has a high temperature close to the ceiling compared to the base of the oven. A high height of the oven results in a low temperature close to the oven base (Manhica *et al.,* 2012b).

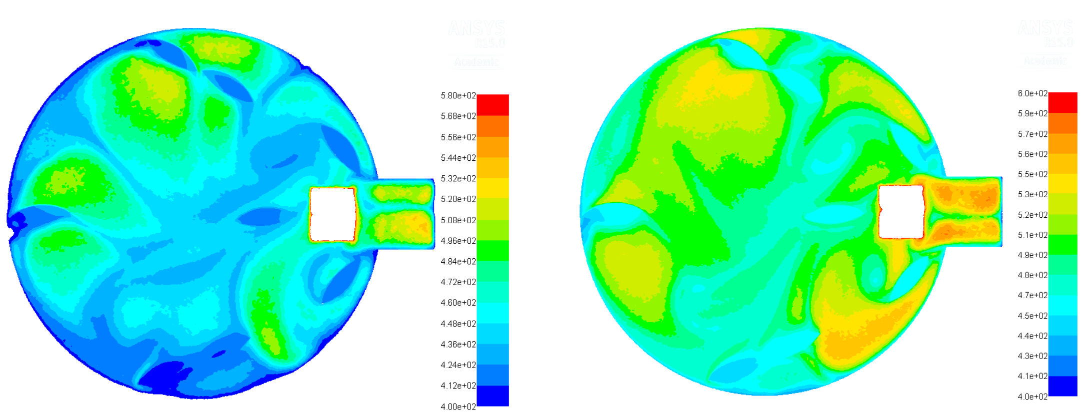
The geometry modification is based on the assumption that by reducing the height of the oven, both the convective and the radiative heat transfer will be improved. In addition, the area of the oven's top surface will decrease due to its hemispherical shape; thus, the loss by conduction through the oven wall will be reduced. The improvement of the circulating heat in the oven will increase the temperature of the hot gases, and it will affect the quality of the bread baking process (Manhica *et al.,* 2012a).

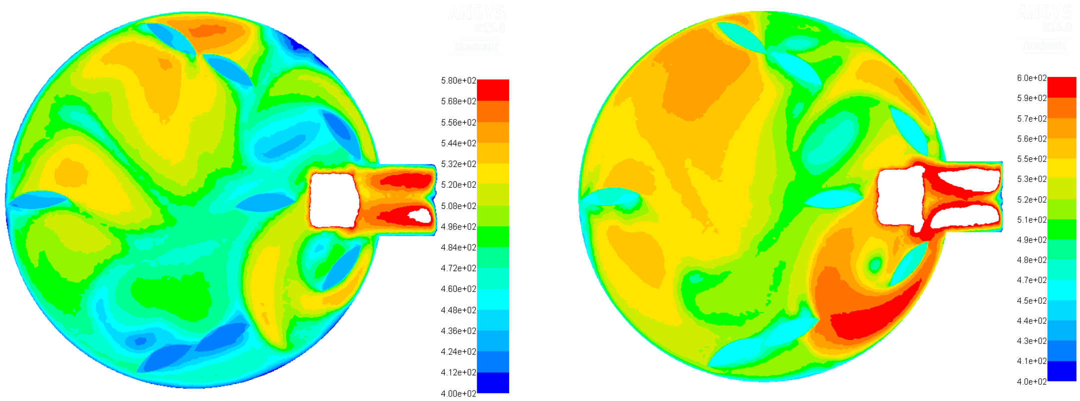
Table 16. Baking time for the original geometry and for the geometry change.

Sample	***Time (min)***	
	Original Geometry	***Geometry change***
1	17.5	~10
2	16.0	8.5
3	14.5	~9
4	20.0	10.5
5	15.0	8.5
6	16.0	~9
7	14.5	~9
8	19.0	10

Shifting the oven chimneys backwards from the original position will likely decrease the flow of the long vortex and thereby increase the heat flux to the bread. The results of the modification (Paper V) are shown in Figure 4.6.1. Figures 4.6.1a and 4.6.1b represent the temperatures in the oven at 1 cm and 5 cm above the oven base for the original geometry and the modified geometry, respectively. It can be seen that the temperature of the oven base is higher in the modified geometry at the bottom line compared to the original at the top line of Figure 4.6.1 when the same amount of wood fuel is used, which indicates a more efficient process.

The temperature inside the oven after the modification is higher compared to the original design. High temperatures are concentrated to the feeding door areas, which suggests that a large amount of heat will spread out from them.





a) *b)*

Figure 4.6.1: Comparisons of the temperature profile of the oven base between the original geometry at the top line and the modified geometry at the bottom line; Figure 2a) at 1 cm and Figure 2b) at 5 cm height from the oven base.

The graph in Figure 4.6.2 shows that the average temperature of the bread samples reaches 372 K (99 °C) between 8 and 10 minutes. In Table 17 the temperature distribution on the bread samples and the heat flux to the bread samples in the oven are shown. The analysis made in conjunction with the Table 17 shows that the heat is distributed along the oven is almost homogeneous. However, sample 4, followed by samples 8 and 1, receive less heat in the oven than the other samples. In general, the temperature in the oven is high and the bread baking processes are decreased in time. In such case, the standard baking process will not be followed properly and processes such as Maillard reaction, browning crust and water vaporisation in the crumb will not be completed (Manhica et al., 2012a). The bread baking process in such condition results in the bread having a good appearance on the outside but not being well baked inside. In order to avoid this situation, the amount of wood burnt must be reduced in the combustion chamber and the temperature should be decreased. This process will not affect the heat distribution in the oven.

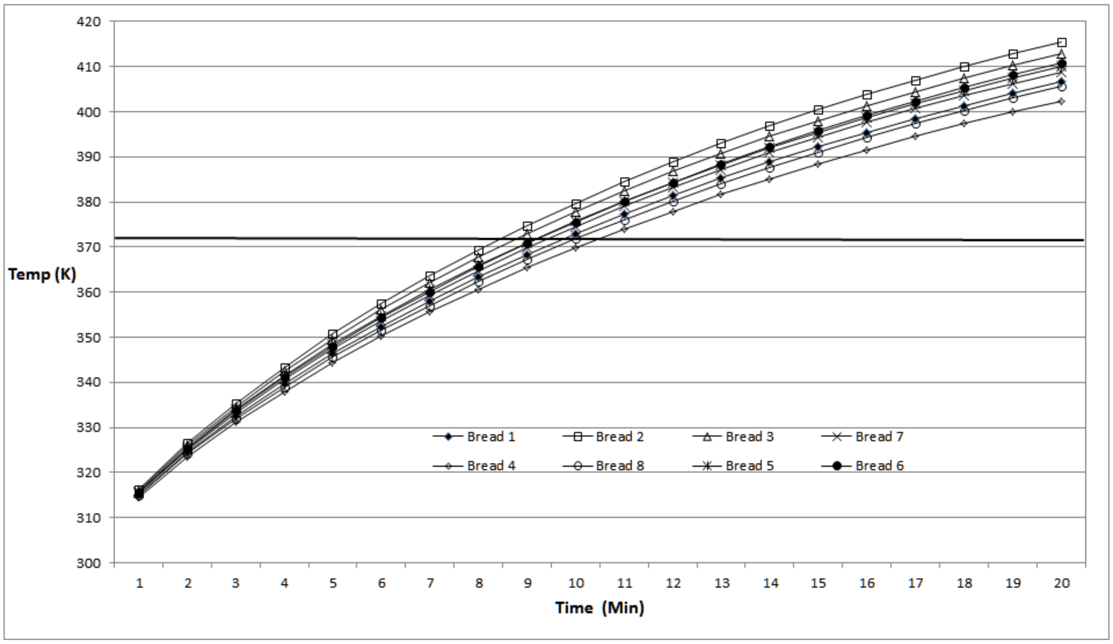


Figure 4.6.2: Graphic representation of the heat distribution on samples

Table 17**:** The temperatures of the bread samples.

Samples	Flux (W)						
	Transient						
	0 min	10 min			20 min		
	Surface and Base temp (K)	Base Temp (K)	Surface Temp (K)	Total Heat Flux (W)	Base Temp (K)	Surface Temp (K)	Total Heat Flux (W)
1	300	394	408	51.13	412	432	28.3
2	300	401	418	55.29	419	440	30.5
3	300	396	416	53.60	414	440	30.0
4	300	390	404	48.93	407	428	27.25
5	300	394	413	52.13	412	436	29.2
6	300	400	413	53.73	419	436	29.5
7	300	398	410	52.30	416	433	28.9
8	300	395	407	51.02	413	431	28.1

CONCLUSIOS

5. CONCLUSIOS

A performance analysis of the bakery furnaces was conducted on the two most commonly used types in the southern part of Mozambique. In terms of specific wood consumption, the indirect type of furnace showed a higher degree of efficiency than the semi-direct type.

The temperature in these ovens is affecting the baking process. An increase in the air flow velocity improves the baking conditions by increasing both the circulation and the effective thermal conductivity of the hot gases within the baking oven.

The feeding door affects the baking process in several ways. When the door is open, hot gases leave the oven close to the upper edge, and the cooler surrounding air enters via the lower edge of the door opening, which results in a lower total flow inside the baking oven. This leads to a shift in the location of the maximum values of several key parameters pertaining to the characteristics of the flow (e.g. turbulence energy and effective heat conductivity in baking oven); from the bottom of the chimney to the top of the fire grate. If these effects are minimised, this will improve both the efficiency of the baking process and the quality of the bread produced in wood-fired bakery ovens.

The experiment performed in the WFBO and the In situ measurements are useful to highlight the problems associated with the bread production process. Mainly, it is necessary to change the temperature distribution in the oven as well as the geometry of the oven to improve the heat transfer during the baking process. The combustion process can be improved by reducing the large amount of heat that is lost between the combustion zone and the baking oven.

The Mathematical model shows high accuracy with experimental data and highlighted the necessity to reduce the large amount of the gases that cross the oven without releasing any heat (the amount of gases leaving already in the grid chimney is as high as 50%) and to change the temperature distribution in the oven.

Geometry changes in the mathematical model predict a better distribution of heat in the oven, leading to a more uniform quality of the bread produced with less energy input.

6. FURTHER WORK

The optimisation of the geometry of the oven is a complex process that needs special attention on many details. The modification in the geometry needs the particular modification on the settings within the computer software. However, it is necessary to maintain the originality of the experimental validated models.

In this work, only part of the oven base was covered with bread and when the number of the samples (bread loaves) is increased to get a more realistic heat distribution, the amount of the data will be large which will require substantial computing resources.

The effect of the feeding door during the baking process has to be taken into account during optimisation because a large amount of the hot gases are lost.

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8. APPENDIX

APPENIX I

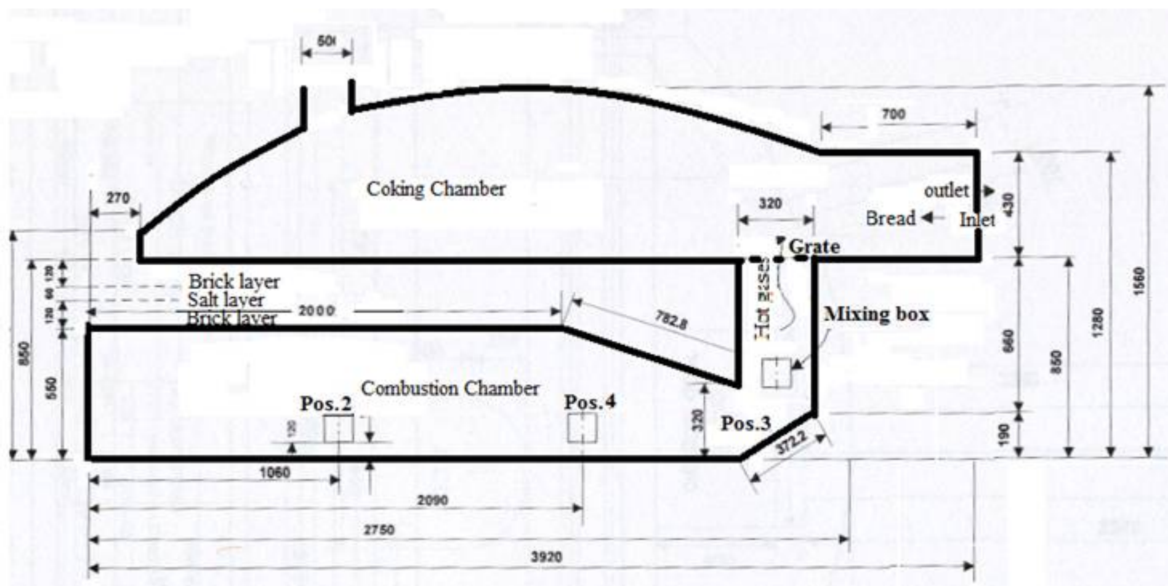

Figure 1: Technical design of the combustion chamber in a semi-direct wood-fired bakery oven, showing the positions at which the temperatures were measured.

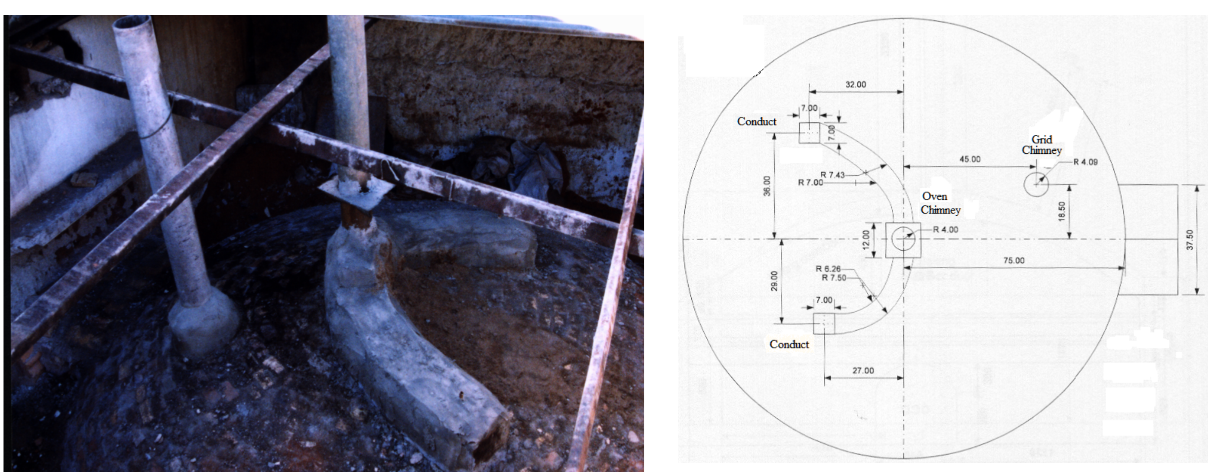

Figure 2: Arrangement of the chimneys above the baking oven in a the wood-fired bakery oven

APPENDIX II

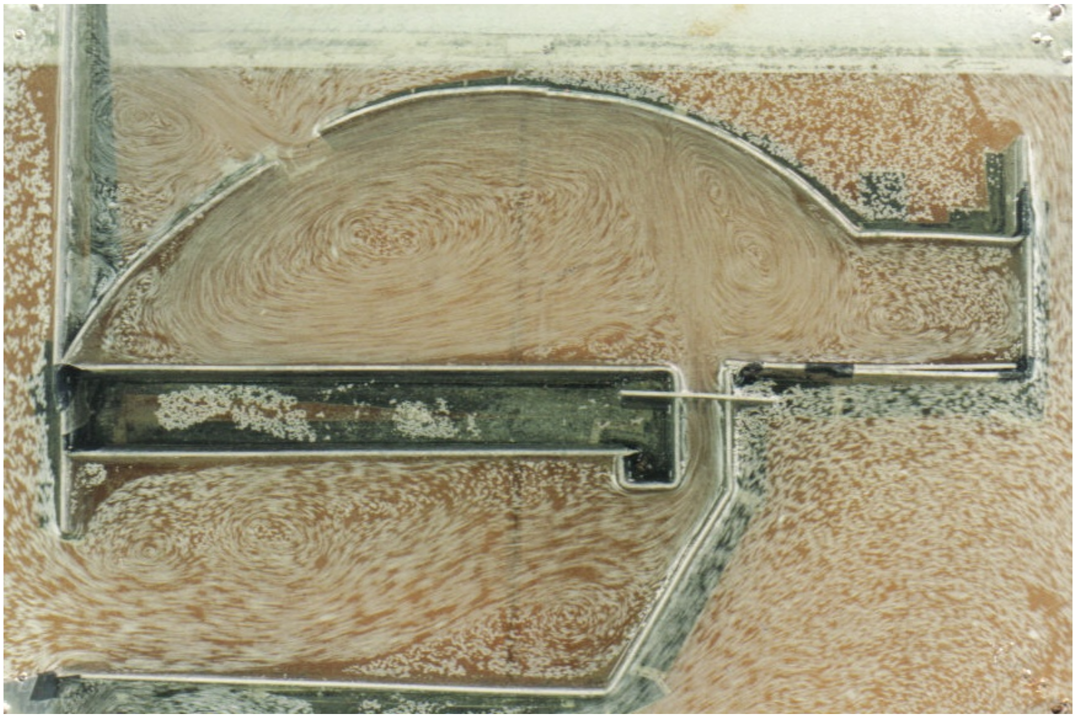

Figure 3: Flow pattern in a baking oven, where the combustion chamber is rectangular in shape

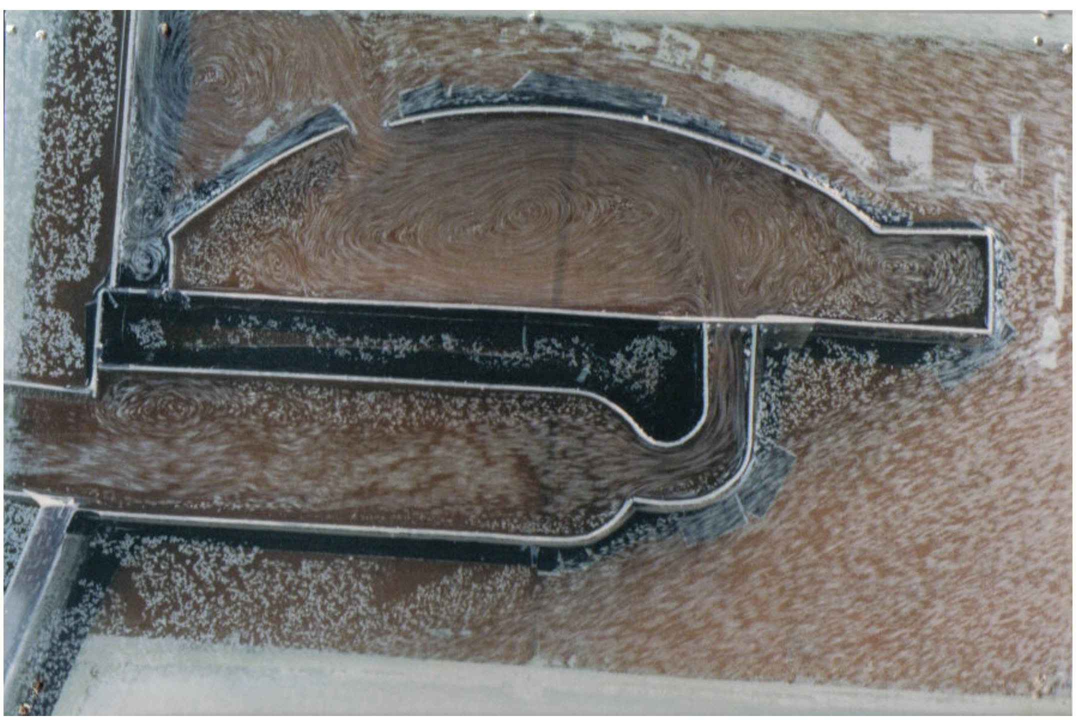

Figure 4: Flow pattern in a baking oven where the combustion chamber has a more rounded shape.