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# Thermal Modelling for A Pilot Scale Pyrolytic Furnace for Production of Carbon Black

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# Thermal Modelling for A Pilot Scale Pyrolytic Furnace for Production of Carbon Black

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**Abstract**
Carbon black (CB) is a very important material useful for various modern applications. There are a lot of attention currently on the extraction of a form of CB obtainable from waste tyres which is usually referred to as pyrolytic Carbon black (CBp). The authors investigated the pyrolysis process of a pyrolytic furnace built for the production of CBp using the thermal numerical principles to standardise the application. SolidWorks@ Flow Simulation software was used to replicate the process by supplying the initial conditions, the boundary conditions and the operating conditions guided by the numerical analysis. The simulated behaviour of the furnace was validated by the real-life experiments performed to produce CBp from the waste tyre.

**Keywords**: Pyrolysis, Thermal modelling, Carbon Black, Simulation and Heat transfer.

## 1. Introduction
Carbon black (CB) has attracted much attention in industrial applications, and its use has been a trend in recent years in the world of scientific research [1]. CB is commonly used as a reinforcing filler and pigment in rubber and plastic products and coatings. In rubber production, CB is used to reinforce rubber and improve abrasion resistance since it is the main reinforcing load in the rubber industry [2]. CB manufacturing processes can be divided into two categories: incomplete combustion and thermal decomposition of hydrocarbons, depending on the presence or absence of oxygen [3]. Many attempts have been made to study the recycling of used tires by pyrolysis methods [3]. Char is the solid residue obtained in the pyrolysis of used tires, also called coal derived from tires. Coal typically consists of fine soot particles, carbonaceous deposits and various inorganic materials [4]. This carbonaceous material contains carbon black (CB between 80 and 90% by weight) and inorganic substances (between 10 and 20% by weight) used in the manufacture of tyres [5,6]. This type of CB is commonly called pyrolytic carbon black (CBp) [7]. It has been found that CBp can perform some of the CB tasks either directly or after certain purification processes [8].

## 2. The experimental Set-Up for CBp production
The built pyrolysis furnace used for the waste tyre pyrolysis runs was sited at the foundry workshop of the Department of Mechanical Engineering, Ota, Nigeria. The physical description of the furnace is as shown in figure 1 below. The refractory bricks enclosure forms the combustion chamber; where the heat generation and expedition take place. At the center of the cubic space lies a barrel-shaped chamber which is shut at the two ends is referred to as the pyrolysis chamber. Four gas burners were arranged along the length of the chamber, two aside [10].

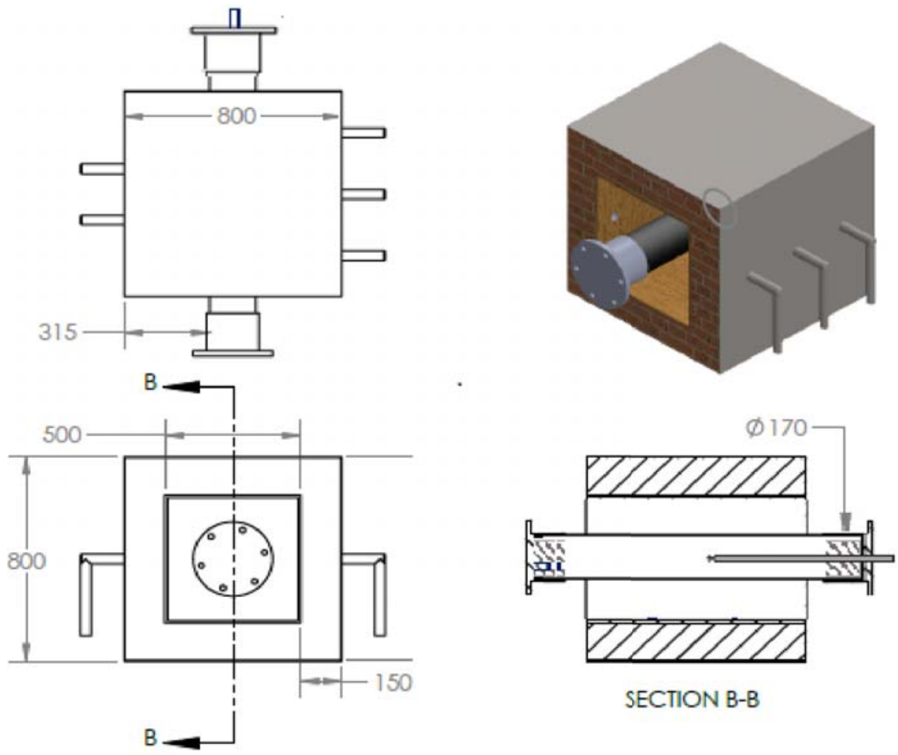


**Figure 1.** Technical drawing of the model Pyrolysis Furnace [9].

## 3. The Thermal Transfer Model

Heat transfer in furnaces cannot be achieved unless there are four (4) interactive processes described by some groups of equations corresponding with each other and solved simultaneously. It should be noted that complete execution of these theoretical analyses is complex though they represent the physical phenomenon but not likely be exact as lots of assumptions will be defined to represent the conditions. Some underlying assumptions include uniformity in temperature of the interacting surfaces, an isothermal condition of operation, a uniform thermal conductivity and homogeneity of materials [11].

Generally, Heat,

$$\boldsymbol{Q = k\Delta tA} \quad (1)$$

where ***k*** is the intensity of Heat Transfer Process and Average Temperature of the burning Flame as $\mathbf{T_g}$ which gives the energy for the heat Transfer rate.

Heat from a combusting gas to the furnace combustion chamber per kg of fuel is given as

$$\mathbf{Q}_c = \frac{k\Delta tA}{B_{Cal}} \quad (2)$$

where $\mathbf{B_{cal}}$ = Burnt Fuel and $Q_c$ is the Heat as a result of the combusting gasses.

$Q_c$ is meant to be transferred by convection to the precursor per Kg of the surface being heated by a unit of fuel. Thus the effect of Qc on the precursor is given by convection heating Surface for a unit surface.

$$\mathbf{q}_c = \frac{\mathrm{Q_c}}{\mathbf{A}} = k\Delta t \quad (3)$$

$\mathbf{q}_c$ = surface heat flux as a result of Heating

***K*** = Heat Transfer per square meter of a heating surface where there exists a unit increase in temperature, i.e. 1$^{o}$C, the larger the Heat Transfer Co-efficient, the stronger the heat transfer process.

## 4. Heat Transfer in The Combustion Chamber of the Pyrolysis Furnace

Temperature Distribution within the Pyrolysis Chamber can be described with the general heat flow equations;

$$\frac{\partial^2 T}{\partial x^2} + \frac{\dot{g}}{K} = 0 \tag{4}$$

$$K\frac{\partial^2 f(x,t)}{\partial x^2} = \frac{\partial f(x,t)}{\partial t} \tag{5}$$

for $0 \le x \le 1$ and $t \ge 0$ where

$$f(0,t) = 1 \tag{6}$$

$$f(x,0) = 1 + x \text{ and} \tag{7}$$

$$\frac{\partial f(x,t)}{\partial x} = 0, \text{ at } x = 1 \tag{8}$$

Where $x$ is chosen to be 0.2 and $t = 0.02$. These values have been chosen to be the mesh size. If the diffusion constant is included, the numerical form of the equation can be written as:

$$[k\rho C_p]\frac{t}{x^2}(f_{i-1,j} + f_{i+1,j}) - [k\rho C_p]2f_{i,j} + f_{i,j} = f_{i,j+1} \tag{9}$$

Where $\frac{K}{\rho C_p}$ is the thermal diffusivity $k$, and $k\rho C_p$ is the thermal conductivity $K$?

$$[K]\frac{t}{x^2}(f_{i-1,j} + f_{i+1,j}) - [K]2f_{i,j} + f_{i,j} = f_{i,j+1} \tag{10}$$

For a hollow cylinder as shown in figure 3, the equation for temperature distribution within its shell by conduction for the radial direction is:

$$[K_{cyl,\ cond}]\frac{t}{(r_n - r_1)^2}(f_{i-1,j} + f_{i+1,j}) - [K_{cyl,\ cond}]2f_{i,j} + f_{i,j} = f_{i,j+1} \tag{11}$$

And that for the L direction is:

$$[K_{cyl,\ cond}]\frac{t}{L^2}(f_{i,j-1} + f_{i,j+1}) - [K_{cyl,\ cond}]2f_{i,j} + f_{i,j} = f_{i,j+1} \tag{12}$$

Where $K_{cyl,\ cond} = \frac{\ln(r_2/r_1)}{2\pi LR}$, $R$ is the thermal resistance, $r$ is the radius of the cylinder, $r_1$ and $r_2$ are the internal and outer radius of the cylinder assuming the cylinder is hollow and $L$ the length of the cylinder [12].

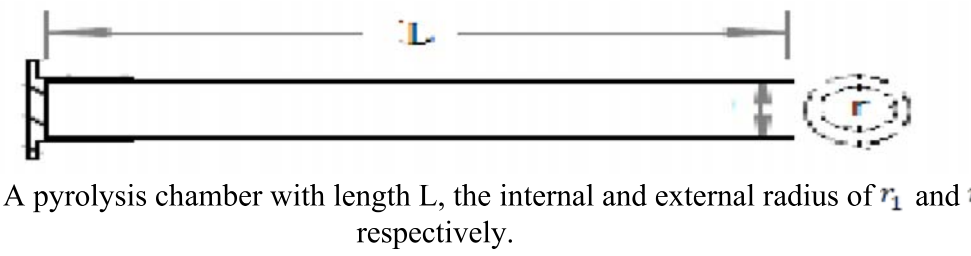


**Figure 2.** A pyrolysis chamber with length L, the internal and external radius of $r_1$ and $r_2$ respectively.

For the cylinder, the equation for temperature distribution by radiation inside it for the radial direction is:

$$[\varepsilon\sigma]\frac{t}{r_1^2}(f_{i-1,j} + f_{i+1,j}) - [\varepsilon\sigma]2f_{i,j} + f_{i,j} = f_{i,j+1} \tag{13}$$

And that for the L direction is:

$$[\varepsilon\sigma]\frac{\varepsilon}{L^2}(f_{i,j-1} + f_{i,j+1}) - [\varepsilon\sigma]2f_{i,j} + f_{i,j} = f_{i,j+1} \quad (14)$$

Where $\varepsilon$ is the emissivity and $\sigma$ is Stephan's constant [13].

Thermal Radiation is the energy emission by a matter as a result of changes in configurations of electrons thus changes in energy via photons by a governing relation known as Stefan-Boltzmann law. Radiation occurs without any medium [14]. This heat transfer mode is prominent in the Pyrolysis Chamber as the flame produced in the combustion chamber is being emitted into the container where precursors was enclosed using radiation [15].

## 5. The Thermal Simulation Analysis

The furnace was simulated using SolidWorks@ Flow Simulation software. The results show that the model is an appropriate method for checking possible means of performance enhancement by supplying the initial conditions, the boundary conditions and the operating conditions guided by the numerical analysis. Figure 3 below shows the temperature distribution by convection in the combustion chamber as a result of hot gas inflow. It is a turbulent kind of flow around the pipe serving as a pyrolysis chamber. It can be deduced that the temperature flow inside is laminar as it can be explained as to the fact that the convection did not get into the (pipe) pyrolysis chamber. Consequently, the convection energy was absorbed as radiation that transfers from around the outside environment of the pyrolysis chamber: this corroborate the theoretical principle of heat transfer in the furnace as established above.

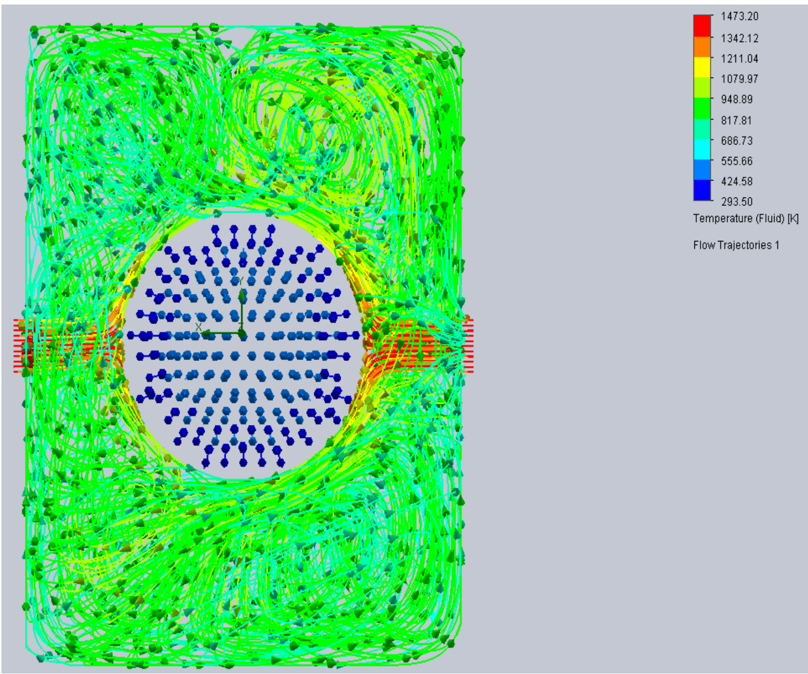


**Figure 3.** The simulated temperature distribution in both combustion and pyrolysis chamber

Figure 4 shows the body temperature variation at an instance of a working temperature using the temperature colour indicator scale. It can be clearly seen that the temperature of the furnace body is very low which validates the theory of thermal resistance of the system as the refractory contains the temperature inside the furnace so as to have a concentration of high temperature inside the combustion chamber and then sequentially, being transferred into the pyrolysis chamber [16].

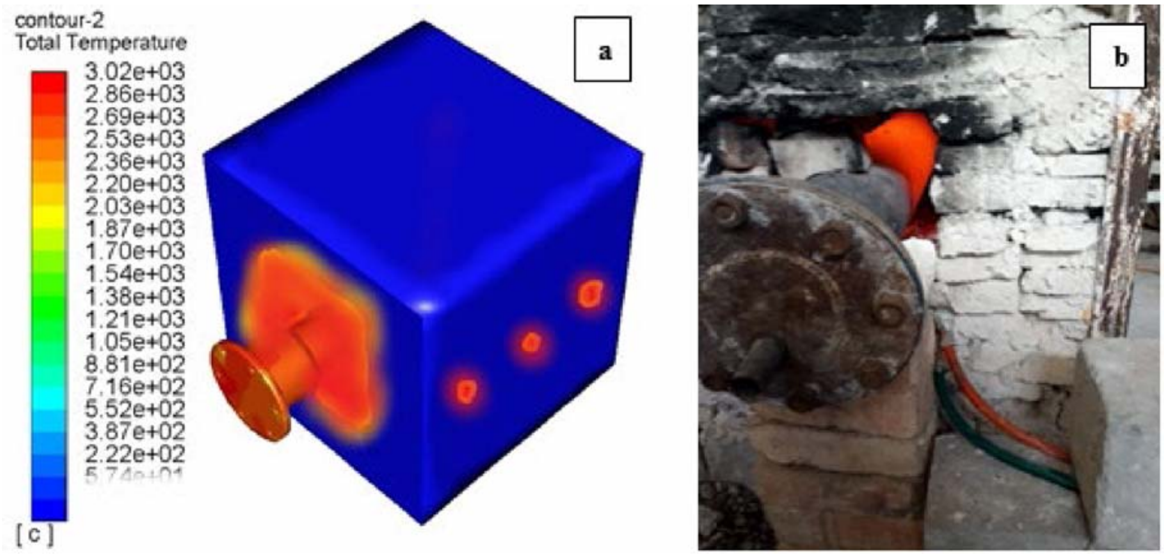


**Figure 4.** The Pyrolysis furnace used to pyrolyse the waste tyres (a) Simulated & (b) Experimental [9]

## 6. Conclusions

The simulation analysis has been furnished with some basic principles of heat and mass transfer provided by the stated numerical analysis. The heat energy was trapped by the kaolin brick linings of the furnace as predicted by the thermal analysis. The Computer simulation shows that the furnace acquired forced convection energy capable of saturating the pyrolysis chamber with enough heat energy that will overcome the thermal resistance of the pyrolysis chamber's material with "$r_1$-$r_2$" thickness. A rapid rate of radiation from the combustion chamber gives rise to the temperature inside of the pyrolysis chamber where a higher concentration of heat energy was conserved for pyrolysis. The simulation result validated the numerical analysis considering the properties of the furnace to meet up with the pyrolysis conditions of the waste tyre to produce the desired products.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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