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COMPUTER AIDED DESIGN OF RECTANGULAR AND CIRCULAR SHAPED ELECTRICAL FURNACES

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ABSTRACT

The software computer package developed was designed to analyse the heat generation and transfer for an electric furnace, and the selection of appropriate heater dimensions and material for the design of cylindrical and rectangular - shaped electric furnaces to meet specific operations at a specified desired temperature and to achieve certain performance level. Datas generated by the software "furnace" are graphed for heater material and can be used to determine electric furnace design for the cross-sectional dimensions and unit power consumption of the heater material, used at various electric heating power output for different desired operating temperatures not exceeding 1000°C.

Keywords: Furnace, heater dimensions, electric power, unit power consumption and furnace efficiency

1.0 INTRODUCTION

Furnace [1] is a structure for heat exchange between a surrounding medium and the charged metals (materials) in which a regular monitoring of temperature at required intervals of time is incorporated.

Furnaces are of various sizes, i.e small, medium and large, depending on the quantity of heat and efficiency required. Design of metallurgical furnaces involve [1] considerations of the mode of operation, its heating mechanism, heat transfer within the furnace, waste utilization, materials and elements of furnaces, capacity and efficiency. Also the energy utilization in a furnace is very paramount in the furnace design analysis.

By their operations, all metallurgical furnaces are classified [2] into melting and heating furnaces and these are of three general types, namely:

(a) Pit type into which the charge is lowered in fixtures or baskets;
(b) Horizontal type into which the work on trays or baskets is pushed on rails or rollers;
(c) Rotating retort type, which can be charged from hopper and tilted to discharge the load.

The energy utilization in an electric furnace is the basis for its design consideration so as to achieve effective performance. It also helps and guides in the determination of the scale of performance for both the metallurgical and economic considerations.

The analysis is used primarily to determine the basic required design parameters of the heater materials for electrical furnaces (rectangular and cylindrical), to predict the heater performance, suitability and its financial implications.

This paper is aimed at applying a software programme called "furnace", written in Visual Basic language, which can be used in generating datas for graphical plottings that can be used for the quick determinations of heater material parameters such as cross-sectional dimensions, lengths, unit power consumption and efficiencies of performance under particular operating temperature conditions and applied electric power.

2.0 THEORETICAL ANALYSIS:

2.1 Heat transfer within the furnace

The generation of electrical energy by electrical resistance of the heating elements involves the transfer of quantities of the energy that leads to temperatures at which most constructional materials would melt or heated up, hence, the adequate protection by heat transfer processes is therefore vital. The heat transfer may occur through conduction, convection or radiation.

2.1.1 Conduction

It can be naturally assumed that the quantity of heat passing through a surface element is proportional to the temperature gradient, area of that surface, time, and a certain coefficient λ, which characterizes the physical properties of the body. This is known as Fourier's law [2] and can be expressed as:

$$Q_x = \lambda A \frac{dt}{dx}, \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

where,
Q_x = rate of heat flow in the positive x – direction;
A = area normal to the x direction of heat flow
λ = thermal conductivity; and
$\frac{dt}{dx}$ = temperature gradient.

The heat flow rate per unit area is called the heat flux. Therefore, Q_x divided by the area A, is known as q_x, i.e

$$q_x = \frac{Q_x}{A}, \; W/m^2 \quad \ldots\ldots\ldots 2$$

Hence, from equation 1

$$q_x = -\frac{\lambda\, dt}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots 3$$

2.1.2 Convection

Isaac Newton [2] proposed a formula to calculate the heat flow from a solid to a fluid or vise versa,

$$Q = \alpha h (t_s - t_m) \quad \ldots\ldots\ldots\ldots\ldots\ldots 4$$

where;
Q = heat flow, kJ/kg
α = heat flow through $1m^2$ of surface;
h = heat transfer coefficient;
t_s = temperature of the solid surface, ^oC;
t_m = temperature of the medium, ^oC

The quantity $\frac{1}{\alpha h}$ is termed the external thermal resistance, hence, from equation 2.6;

$$Q = \frac{t_s - t_m}{R_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots 5$$

where $R_m = \frac{1}{\alpha h}$ = external thermal resistance.

2.1.3 Radiation

By the Stefan-Boltzman's law [2], the maximum heat flow at a given temperature is emitted by a black body.

$$Q = A \sigma_o T_o^4 \quad \ldots\ldots\ldots\ldots\ldots\ldots 6$$

where;
Q = heat flow, W;
A = common area of radiation surface, m^2;
T = temperature, ^oC; and
σ = radiation constant.

With radiant heat exchange between two bodies, the resulting radiant heat flow from one body to another is usually expressed by this expression;

$$Q_{12} = \sigma_{rad} \left(T_1^4 - T_2^4\right) A \quad \ldots\ldots\ldots\ldots\ldots\ldots 7$$

where;
A = common area of radiation surface and
σ_{rad} = radiation constant.

2.2 ENERGY UTILIZATION IN AN ELECTRIC FURNACE

Electric furnaces are employed in metallurgical processes for the purpose of heating materials using electric energy, known as electrothermal processes. The use of electric energy for heat generation offers the following advantages;

(a). Concentration of a high energy in a small volumes resulting in high temperature;
(b). Easy control of temperature and temperature distribution in the furnace space, which makes possible uniform heating of large bodies;
(c). Heating can be combined with other useful effects produced by electric energy;
(d). Since no fuel combustion takes place in electric furnaces, the pressure in the furnaces can be used as a factor for controlling the metallurgical process in vacuum and compression electric furnaces.

The electric heating/melting plant should be supplied with electric energy of definite parameters. Generally, the electric heating or melting plant is a combination [3] of thermal and electrical equipment, which usually consists of three principal parts, namely:

(a) the furnace proper;
(b) an electric substation accommodating the power source and all the electrical equipment;
(c) a control board.

The material of the heating element should have the following properties: high electric resistivity $\left(\alpha_\rho, K^{-1}\right)$, high melting point which should not undergo phase transformations on heating or cooling and, low cost.

The heating elements of furnace can be made of metals or non-metals [3] and of resistance alloys e.g Ni-Cr, Fe-Cr-Ni and Fe-Cr-Al and high melting metals like Molybdenum, Tungsten, Tantalum. The heaters can be fastened to the plant in a zig-zag form either on the shelves of the roof, on metallic hooks, on ceramic shelves or in the slots of the hearth.

The energy [4] of the heater is given as;

$$W = I^2 R t \quad \ldots\ldots\ldots\ldots\ldots\ldots 8$$

where;
I = current, Ampere;
R = resistance, Ω; and
t = time, seconds.

The heating effect can either be open metallic heating in which the heat flux density is 5 – 20 kW/m^2 at

1300°K or Tubular heaters in which the heat flux density is 80 – 120 kW/m^2.

The operation of an electric heating or melting plant indicates that energy is lost both as a heat in the furnace space and as electric energy in other component of the plant. For this purpose, the heat balance of the plant should be complemented with an energy balance of one of two types [4].

(a). An energy balance which compares the quantity of electrical process energy,

supplied to the furnace from a power system during a certain period with the

assumptions made of this energy for the same period, is:

$$W_s = W_{us} + W_{aux} + W_{hl} + W_{el}$$

$$= \frac{1}{\varsigma}\left[W_{us} + W_{aux} + W_{hl}\right] \quad \ldots\ldots 9$$

$$= \frac{W_{us}}{\varsigma_o}$$

where;

W_s = electric energy taken from the power system to carry out the technological process; (kJ or Kw.h)

W_{us} = useful energy consumed in the process;

W_{aux} = the energy spent to heat the lining and structures of the furnace;

W_{hl} = energy to compensate heat losses from the furnace space;

W_{el} = energy to compensate electrical losses in the components and circuit of the plant;

ζ = electrical energy efficiency of the plant;

ζ_o = total energy efficiency of the plant.

(b). A balance [4] of power which compares the power taken from the system at a given instant of time with the power consumed in the electric plant is given as:

$$P_s = P_{us} + P_{aux} + P_{hl} + P_{el} \quad \ldots\ldots\ldots 10$$

where;

P_s = the electrical power taken from the power system to carry out the process; (MW)

P_{us} = useful power consumed in the process;

P_{aux} = power spent to heat the lining and furnace structures;

P_{hl} = power compensating heat losses from the furnace space;

P_{el} = power spent to compensate electrical losses in the components and circuit of plant.

It should be pointed out that:

(a). The two balances contain similar output and input items, but may be different in proportions with one another during various time moment of the heating process.

(b) Electrical balance did not include electrical energy outside the furnace, i.e in the auxiliary mechanisms, stirrers etc.

For the heating period, the energy balance [5] is;

$$\left(P_r - P_{hl}\right)\tau_2 = i m_o + P_{hl}\tau_1 \quad \ldots\ldots\ldots 11$$

where;

P_r = the average power supplied to the furnace, kW;

τ_1 = the time when the furnace is prepared to heating (charging period) , hours;

τ_2 = the heating or melting time, hours.

$$\text{i.e } \tau_2 = \frac{i m_o + P_{hl}\tau_1}{P_r - P_{hl}} \quad \ldots\ldots\ldots\ldots 12$$

m_o = the mass of the charge, kg;

i = the theoretical energy required to heat a unit mass of charge, i.e unit enthalpy, (kW.hr/kg);

P_r = the average power supplied to the furnace, (kW);

$$P_r = K_{ut} S_r Cos\phi \eta_e \quad \ldots\ldots\ldots\ldots 13$$

S_r = the rated power of the power source ,kVA;

$Cos\phi$ = cosine factor;

K_{ut} = the coefficient or power utilization of the converter during the heating periods;

$$K_{ut} = \frac{1}{P_r \bullet \tau_2}\int_0^{\tau_2} P(\tau)d\tau \quad \ldots\ldots\ldots\ldots 14$$

The unit consumption of electric energy is found from the energy balance of the plant as given in equation (9)

$$W_{un} = \frac{W_s}{m_o} = \frac{1}{\eta_e}\left(i + i_p + \frac{P_{1hl\tau_1}}{m_o} + \frac{P_{2hl\tau_2}}{m_o} + \frac{P_{3hl\tau_3}}{m_o}\right) \ldots 15$$

where;

W_{un} = unit consumption of electric energy, (kWhr/kg);

P_{hl} = power compensating heat losses from the furnace space for the time when the furnace is prepared to heating, the heating or melting time, and the cooling time.

τ_1 = the time when the furnace is prepared to heating, hours

τ_2 = the heating or melting time, hours

τ_3 = the cooling time, hours

η_e = the efficiency of the furnace

i_p = the theoretical required energy for the technological process carried out during the period τ_3 (kW.hr/kg).

The lining design consideration is very important in the design of furnaces with the appropriate heater dimensions for economic reason, since increasing the lining thickness will lead to increase in heater dimensions for effective heating process, which eventually leads to a bulky size and increase in cost.

With high-temperature indirect-action resistance furnaces, it is often impossible to select refractory and heat insulating materials, which can stand properly the high temperature existing in the furnace. In such cases, use is made of heat –insulating graphite or metallic screens. The screens are also used to diminish the thermal inertia of the lining, to lower gas adsorption in vacuum furnaces, or to concentrate heat flows in the furnaces with focusing screens called optical furnaces. The screens serve as a reflector; its temperature has no effect on heat exchange in the furnace and can be lowered to zero making it possible to have a screen of high reflectivity.

2.3 ANALYSIS OF HEATING ELEMENTS

The calculation of heating elements [5] is usually started by selecting the allowable power (q, per unit area) of the outer surface of a heater (kW/m^2), which depends on the following characteristics;

(a) Maximum allowable temperature for the selected material of heating elements in long operation;
(b) Maximum temperature of heat-absorbing surface of the heated charge or medium;
(c) Conditions of heat transfer from the heater to the heated charge or medium.

In the indirect resistance furnaces operating in a radiant mode, the condition of heat transfer from heaters are characterized by the degree of screening of the heaters, the reduced coefficient of radiating surfaces of the heaters and heated charge.

The thermal energy liberated [5] in the heaters of the furnace is transferred by radiation to the surrounding bodies, i.e lining and charge.

The heat transfers from the heater to object and from heater to lining for these plants are;

$$\left.\begin{aligned} \Phi_{h-o} &= P_{us} = \sigma_{h-o}\left(T_h^4 - T_o^4\right)S_o \\ \Phi_{h-l} &= P_{hl} = \sigma_{h-l}\left(T_h^4 - T_l^4\right)S_h, \end{aligned}\right\} \quad \text{........ 16}$$

and the temperature of the heater can be obtained as follows;

$$T_{h\,\max} = \sqrt[4]{T_o^4 + \frac{P_{us}}{\sigma_{h-o}\,S_o}} \quad \text{........ 17}$$

and the lining temperature;

$$T_{l\,\max} = \sqrt[4]{T_o^4 + \frac{P_{us}}{\sigma_{h-o}\,S_o} - \frac{P_h}{\sigma_{h-l}\,S_h}} \quad \text{........ 18}$$

In the arrangement considered, with an ideal heat insulation, $P_{hl} \cong 0$ and $P \cong P_{us}$ and also equal areas of the heating surfaces of the heated body and heater i.e $S_o \approx S_h$, hence;

$$\Phi = \frac{\sigma_o}{\left(\frac{1}{\varepsilon_h}\right) + \left(\frac{1}{\varepsilon_o}\right) - 1}\left(T_h^4 - T_o^4\right)S \quad \text{..........19}$$

and;

$$q_{id} = \frac{\Phi}{S_h} = \frac{\sigma_o}{\left(\frac{1}{\varepsilon_h}\right) + \left(\frac{1}{\varepsilon_o}\right) - 1}\left(T_h^4 - T_o^4\right) \quad \text{...... 20}$$

where q_{id} is the unit surface power of an ideal heater.

The unit surface power of a real heater can be calculated by introducing a correction factor K_{ef} into equation 20 to obtain;

$$q = q_{id}\,K_{ef} \quad \text{..................... 21}$$

The value of K_{ef} for various types of heaters [9] can be taken as follows;

Wire spirals:
Semi-closed in slots of lining............0.16 – 0.24
On shelves and tubes.......................0.30 – 0.36
Zigzag wire heaters (on tubes)............0.60 – 0.72
Zigzag strip heaters ....0.38 – 0.44

In calculating the heating value, it was assumed that the entire electric energy taken from the mains is released, as heat in the heating elements and that the heat is transferred to the object being heated and the furnace lining.

If the cross-sectional area of a heater is S, then the product of its perimeter Π and the area is given as;

$$S = \rho\left(\frac{p}{v}\right)^2 \bullet \frac{1}{q} \bullet 10^3 \quad \text{........22}$$

for a round heater of diameter D;

$$D = 10\,000\sqrt[3]{\frac{4}{\pi^2}} \bullet \sqrt[3]{\rho\left(\frac{p}{v}\right)^2 \frac{1}{q}},$$

$$D \approx 7400\sqrt[3]{\rho\left(\frac{p}{v}\right)^2 \frac{1}{q}} \quad \text{....... 23}$$

and for a rectangular heater of thickness a;

$$a = \frac{10\,000}{\sqrt[3]{2k(k+1)}}\sqrt[3]{\rho\left(\frac{P}{V}\right)^2 \frac{1}{q}} \quad \text{....... 24}$$

where;
P = rated power, kW;
V = the rated voltage, V;
ρ = the electric resistivity of the heater material at furnace temperature, Ωm;
k = the width to thickness ratio for heaters of a rectangular cross-section.
q = modified unit surface power of heater

The unit consumption of heater material are;

For cylindrical heaters;

$$M_u = 0.25\, d\, \frac{D}{q} \quad \text{......... 25}$$

and for rectangular heaters;

$$M_u = 0.5\, \frac{k}{k+1}\, d\, \frac{a}{q} \quad \text{........26}$$

where d is the density of the material

3.0 COMPUTATIONAL METHODS

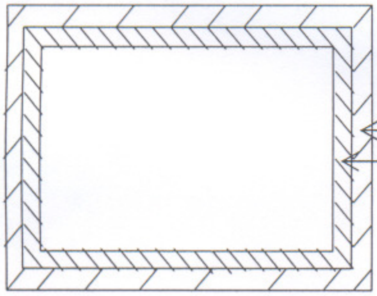

Fig. 1a.: Cross-section of rectangular-shaped furnace showing the lining materials

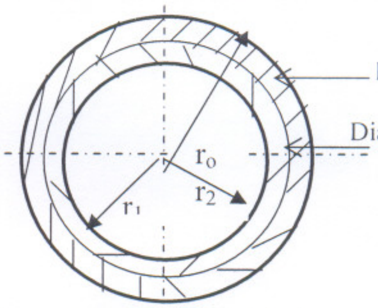

Fig.1b: Cross-section of a cylindrical shaped furnace showing the lining materials

The figure 1 (a and b) above shows the cross-section of the furnace. The lining material is made up of diatomite and fireclay to prevent heat lost. The body of the furnace is made up of heat-resistant, refractory steels and alloy, also to minimize heat losses and to prolong the service life of the furnace.

The developed software programme termed "furnace" is capable of handling any furnace type; cylindrical or rectangular, which can either be gas fuel fired, liquid fuel fired, solid fuel fired, or electrically heated. The programme was used to generate the following furnace parameters based on the required specified furnace productivity and the billet dimension:

For the rectangular shaped furnace;

Dimensions:	1000mm square
Length:	1600mm
Fireclay thickness:	75mm
Diatomite thickness:	75mm
Internal furnace dimensions:	1250mm square
Internal volume:	$1.6m^3$

Wire spirals, semi-closed in slots of lining and the dimension of the equivalent cylindrical shaped furnace of the same internal volume are;

Length:	1600mm
Outside diameter, d_o:	1200mm
Fireclay thickness:	35mm
Diatomite thickness:	35mm
Internal diameter, d_i:	1130mm
Internal volume of the furnace:	$1.6m^3$

Wire spirals, semi-closed in slots of lining.

The developed furnace programme, which is in two phases consist of the input and the output unit. In the first phase, the input unit includes information needed to run the programme. These include number of electrical phases, electrical power, electrical voltage and temperature of interest. The output unit would after performing the necessary calculations give all the design parameters such as the heater density, heater diameter/thickness, heater length, heat flow surface density, unit consumption of heater material, mass of heater and the maximum heater temperature. The maximum heater temperature only serves as a guide to ensure that the heater material is capable of attaining desired temperature.

In the second phase, the input unit comprises of billet dimensions, lining material thicknesses and the furnace productivity. The output unit gives the following results, after performing the necessary calculations, furnace dimensions, percentage of furnace volume occupied, number of billets, mass of billet, efficiency and the heating time.

In this paper, only the electrical heated furnace was presented, using the developed VISUAL BASIC software programme .

4.0 RESULTS AND DISCUSSION

Figures 2 to 9 can be used to estimate all the required parameters when designing for furnaces to operate at a particular temperature of interest. Figure 2 is the graph of heater diameters versus the supplied powers. It can be seen from the graph that as the supplied powers and the desired temperatures increase, the heater diameters increase. Figure 3 is the graph of heater lengths versus supplied powers. From this graph, as the supplied powers and the desired temperatures increase, the heater lengths also increase. Figure 4 is the graph of the unit consumption of heater against the supplied power. As usual, an increase in i.e $R = \dfrac{\rho l}{A}$, as the supplied power and the desired temperature increase, the resistance of the heater material decreases, giving rise to an increase in the area and other related parameters. Figures 5 to 7 are the same as that of figures 2 to 4. Figures 2 to 4 are only applicable to cylindrical shaped electric furnaces, while figures 5 to 7 are for the rectangular shaped electric furnaces.

Figure 8 is the graph of furnace efficiency versus percentage volume occupied. For the same percentage volume occupied of 41.2%, the cylindrical furnace efficiency is higher than the rectangular furnace efficiency. This is maintained until a critical value of percentage volume occupied of 46.7% is reached., at which the cylindrical furnace efficiency is lower than the rectangular furnace efficiency for further increase in the percentage volume occupied. The furnace efficiency at this critical percentage volume occupied is 55%. Beyond this critical value of percentage volume occupied, rectangular shaped electric furnaces give better result in terms of efficiency, which is an advantage especially when the furnace is designed for maximum volume occupied to minimize cost.

Figure 9 is the graph of heating time versus percentage volume occupied. As the percentage volume occupied increases, the heating time also increases to give enough time for temperature homogeneity of the charged metals.

In designing for an electric furnace to operate at a maximum temperature of 500°C, with a single-phase electric power and voltage of 22.5kW and 230 volts respectively and for a cylindrical shaped electric furnace, from figures 2 to 4, the heater diameter gives 4.5mm, while heater length is 27m, and the unit consumption of heater material is 420kg/hr.

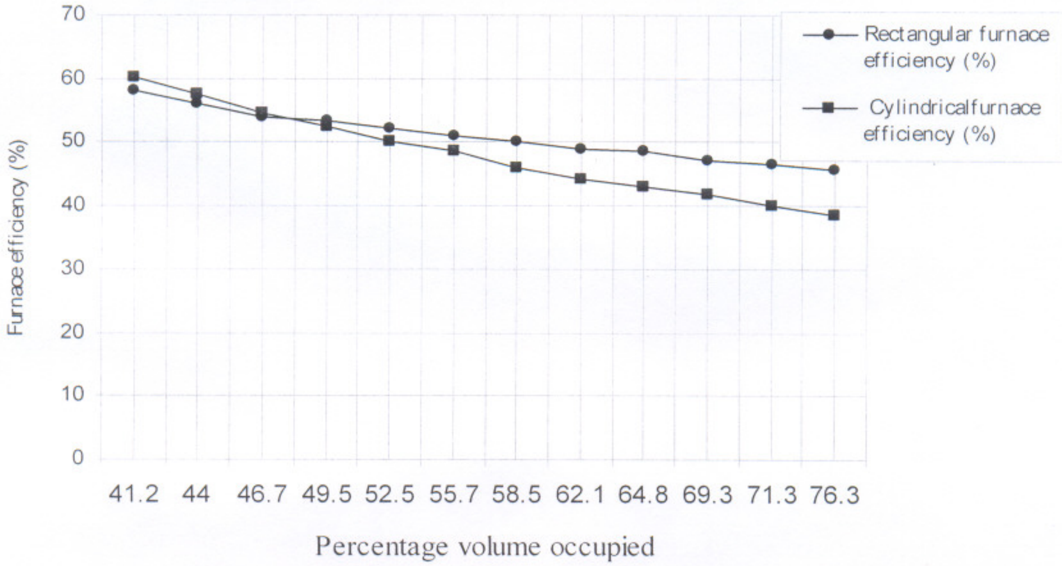

Fig. 8: Percentage volume occupied versus furnace effeciency

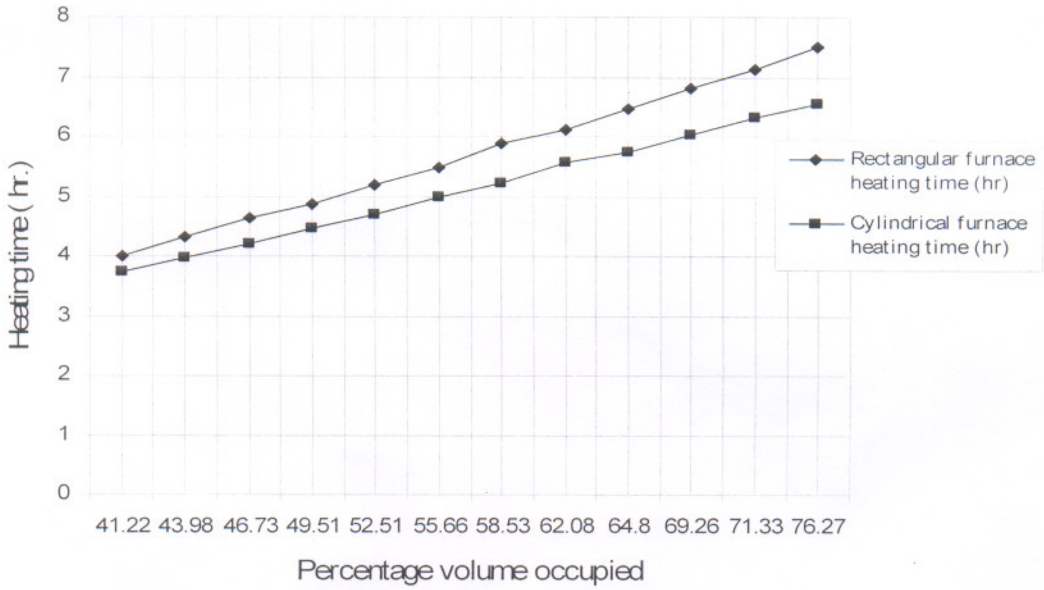

Fig. 9: Percentage volume occupied versus heating time

Similar results can also be estimated from figures 5 to 7 when designing for a rectangular shaped electric furnace to operate under the same conditions.

5.0 CONCLUSION

The computer-aided design for furnaces give details of the materials for the building of furnaces to minimize heat losses and to prolong the life span of the designed furnace. The graphs developed can be used to generate the heater materials parameters such as heater length, heater diameter, heater thickness, unit heater consumption at any temperature of interest not exceeding 1000°C. The programme is made flexible to handle any furnace problems based on the design necessities, the operating condition and the most appropriate furnace building materials for effective performance and service life.

7.0 REFERENCES

1. **Krivandin, V. and Markov, B., (1980)** Metallurgical Furnaces, Mir Publishers, Moscow.

2. **Kazantsev, E. I., (1977)**, Industrial Furnaces, Mir Publishers, Moscow.

3. **Egorov, A. V. and Morzhin, A. F., (1975),** Electric Furnaces for Steel Making, Moscow.

4. **Krivandin, V. A., Molchanov, N. G. and Solomentsev S. L.,(1962),** Metallurgical Furnaces, Metallurgizdat, Moscow.

5. **Chapman, W. A. J., (1975)**, Workshop Technology; Part III, The English Language Book Society and Edward Arnold (publishers) Ltd, London.

6. **Sparrow, E. M. and Cess R. D., (1967),** Radiation Heat Transfer, Wadsworth Publishing Company, Inc., United States of America.

7. **Bayazitoglu Y. and Özi∏ik, M. N., (1976),** Elements of Heat Transfer, McGraw–Hill Book Company, United States.

8. **Andrew, D. D., (1989)**, Computer Aided Machine Design, Prentice–Hall International Ltd, UK.

9. **Katsevich L. S., (1959),** Calculation and Design of Electric Furnaces, Gosenergoizadat, Moscow – Leningrad.

10. **Lock, G. S. H., (1996)**, atent Heat Transfer – An Introduction to Fundamentals, Oxford University Press, New York.

11. **White, F. M., (1988)**, Heat and Mass Transfer, Addison – Wesley Publishing Company, United States of America.

12. **Douglas, J. F., Gasiorek, J. M. and Swaffield, J. A., (1992),** Fluid Mechanics, Second Edition, The English Language Book Soceity and Longman Publishers Ltd., Singapore, pp 150 – 167.

13. **Fashade, O. A., (1985)**, Introduction to Thermodynamics, Africa Photo Press Nigeria Ltd., pp 250 – 300

14. **Abioye, A. M., (2001)**, "Computer Aided Design of Power Transmission Elements", M.Eng. Report, University of Ilorin, Ilorin, Nigeria,.