COMPARATIVE EVALUATION OF ROTARY AND CRUCIBLE MELTING FURNACES EFFICIENCIES

By

J. K. Akinluwade and M. O. Adeoye
Department of Materials Science and Engineering,
Obafemi Awolowo University,
Ile-Ife, Osun State 220005. Nigeria.

ABSTRACT

The paper studies the efficiencies of rotary and crucible furnaces. The two furnaces lined with fireclay refractory use diesel as their source of fuel. In this paper structure-operation and fuel type-fuel combustion approaches are used to determine the efficiencies. The efficiency values for rotary and crucible furnaces are found to be 72% and 68% respectively.

Keywords: rotary furnace, crucible furnace, energy point, furnace efficiency.

1.0 INTRODUCTION

Mankind from long ago has been involved in the production of metallic tools for use in agriculture, warfare, ornament making and so on. Such production usually involved the use of heat generated from a source, confined to a compartment (i.e., furnaces), and safely transferred to the workpiece for the purpose of heating, re-shaping, refining, melting and so on.

Furnaces are characterised by the ability to generate large amount of heat energy sufficient to soften or melt hard objects such as metals.

Metallurgical furnaces can be classified into heating and melting furnaces [1]. In any application, the interest in a furnace is not only in it heating or melting a work piece but also in *how well* it does so, the level of fuel economy, duration of operation as well as the level of quality of products. Hence it is required that a furnace carry out its intended function with an acceptable level of efficiency. In melting applications where it is required that the heating system generate as much heat energy as possible and that the refractory conserve as much heat energy as possible, the efficiency is considered as the extent to which a furnace satisfies these requirements. In heating furnaces, the essential requirements are that a furnace should be able to attain a specified temperature value, heat or cool at a specified rate, and soak or hold the charge at a desired temperature for a specified time. The efficiency is therefore the extent to which a control can be exercised over these features. Although different types of furnaces exist, their components are essentially the same; these are the heating system and the refractory system. Both systems work together to achieve successful heating or melting of desired work pieces.

Rotary and crucible furnaces are the commonest fuel-fired furnaces found in most foundries in third world countries; therefore, rotary and crucible (bale-out type) furnaces of melt capacities 100 kg and 80 kg respectively were considered in this study. They both used diesel as source of fuel and were lined with fireclay refractory. In furnace operations, it is commoner to calculate efficiency values from heat transfer within the furnace without giving attention to the effect of the furnace structure and the nature of production operation which are peculiar to each furnace. This study therefore investigates the efficiencies of the crucible (bale-out type) and the rotary furnace using two approaches: the Structure—Operation method and the Fuel Type and Fuel Combustion method.

2.0 METHODOLOGY

2.1 Method I: Structure—Operation

This approach was based on analysis of the furnace structure and the production operation. The structural analysis involves the number of openings, their location, and capacity for conserving heat energy. The production operation, on the other hand, involves a measure of how much heat an opening conserves depending on frequency of exposure to the outside environment, as well as the degree of quality of melt owing to some features of production operation.

The physical structure of both furnaces consists of the shell (steel outer casing) and the internal refractory lining (aluminosilicate). Other accessories are auxiliary to the furnace unit. A point in the structural framework of any of the two furnaces that is characterized with the ability to let out heat energy in any form (conduction, convection, or radiation) is described here as an *Energy Point*. The occurrence of an Energy Point may be either structurally *inadvertent* or *intentional*. Therefore, any openings found in the structure of the furnaces, inadvertent or intentional, qualify as an Energy Point. When the designer did not intend that an opening to be present in the final furnace structure we refer to it as an *Inadvertent Energy Point*. They include such microscopic openings as discontinuities in weld beams, bolted joints, cracks and other miscellaneous structural flaws occasioned by fabrication processes. *Intentional Energy Points*, on the other hand, are the openings which the designer deliberately introduced as a matter of necessity in the design. Such openings serve as outlets or inlets for various materials. The Energy Points identified in the two furnaces are shown in Figures 1 and 2, while Tables 1 and 2 give the designation and description of each energy point. There are five Energy Points in the shell of each furnace.

2.1.1 Features of Energy Points

The two furnaces of this study were studied and the following features were observed with reference to Energy Points for both furnaces.

All *Intentional Energy Points* are observed to occur in a definite number and each served a definite purpose; have definite size or dimension (the sizes would generally vary depending on furnace capacity); have specific location; and have different *Energy Potential* (this is defined here as the capacity of each Energy Point for conserving heat energy). *Inadvertent Energy Points* occurred in a random and relatively infinite number. However, for simplicity, the location of the *Inadvertent Energy Points* was fixed as an arbitrary single point representative of all such points and the dimension was taken as microscopic for the purpose of reference and evaluation.

Analysis for Energy Potential was based on the capacity of each Energy Point to conserve a fraction of the unit energy the heating system makes available. The magnitude of the Energy Potential values was considered as a combined function of the following:

I. [1]Mode of production operation.
II. Function of each Energy Point.
III. Location of each Energy Point.
IV. Effective surface area of exposure
V. Duration and frequency of exposure

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[1] The production operation of both furnaces was divided into two: Mode I and Mode II. Mode I is the form of production whereby the charge is loaded once, the furnace is fired, and after melting, the melt is discharged at one go. Mode II operation is one in which the charge is continually supplied and the molten metal is intermittently discharged or tapped. Mode II operation normally spans a longer period and is more prominent.

The method used involves ranking each Energy Point down a hypothetical Energy Scale based on its propensity for conserving heat energy. This propensity is based on the five items mentioned above. The hypothetical Energy Scale rates from 0.0 to 5.0 and is graduated in 0.5 divisions correspondence to the total number of Energy Points in each furnace. Using this scale, each Energy Point was ranked in steps down the scale in the order of propensity for heat conservation during a given mode of production operation.

Analytical values obtained here take into consideration the structure of each furnace and the mode of production operation alongside tendency for heat loss. The step-by-step analysis for determining the energy potential of the various Energy Points in each furnace type is presented as follows.

2.1.2 Rotary Furnace

2.1.2.1 Mode I: Production Operation

[2]**E** (Furnace Body) conserves the most heat and was ranked 4.5 on the Energy Scale. This is because it is an *inadvertent energy point.* It thus conserves the most heat. **C** (Emergency Spout) conserves next to **E**. **C**, being an emergency opening may not be opened in Mode I operation. However, in the event of blockage of **B** (Pouring Spout), **C** is opened and **B** remains blocked while tapping is done through **C**. In essence, same probability exists for the blockage of both **B** and **C** so that they were ranked on the same level 4.0. From observation of the production operations, **B** or **C** is not opened until the charge has melted, so both conserve heat better than **A** (Burner End) which is always opened throughout the operation. Consequently, **A** was ranked 3.5. **D** (Exhaust/Charging End) conserves next to **A** and, of course, least. It should be noted that exhaust gases carry heat away from the hearth owing to an axial stream of air-current that issues from **A**, blows across the furnace bed and exits through **D**. **D** is thus ranked 2.5.

2.1.2.2 Mode II: Production Operation

In Mode II production operation, **E** (Furnace Body) still conserves the most heat and was ranked 4.5 on the Energy Scale. **A** (Burner End) conserves heat next to **E** and was ranked 4.0 on the scale. Both **B** (Pouring Spout) and **C** (Emergency Spout) conserve heat next to **A** and were ranked 3.5. They conserve heat more than **A** because on prolonged operation, tapping is done periodically and both the

[2] The alphabets refer to Energy Points as denoted in Figure 1

removal of hot melt and the attendant intermittent exposure of the combustion chamber imply removal of considerable heat from the combustion chamber. **B** and **C** were ranked on the same level because during Mode II operation, it is not unlikely that one of **B** and **C** might block. In such a situation, the other will be promptly opened to continue pouring for approximately the length of time it took the first to block and subsequently or alternately like that until the end of the production session. Ranking **B** and **C** on same level thus compensates for the equal likelihood of blockage and of exposure of the furnace space via either opening. **D** (Exhaust/Charging End) ranks next and, of course, least. It does not immediately follow **B** and **C** on the Energy Scale for the same reason given in the case of Mode I operation. **D** was rated 2.5.

2.1.3 Crucible Furnace

2.1.3.1 Mode I: Production Operation

R (Furnace Body) conserves heat best and was ranked 4.5 on the Energy Scale. Both **Q** (Lid Opening) and **T** (Emergency Opening) conserve as much heat as **R** and were ranked on same level on the scale. In a mode I operation, both **Q** and **T** *act* as inadvertent energy points. Since both would normally not be opened in this mode, rigid blockage is provided at both sites. At **Q**, the lid (with its refractory lining) fits well into the cylindrical body shell while at **T** the opening is tightly shut with no anticipation of opening. The resulting effect is that both **Q** and **T** conserve maximally — as much as **R**.

S (Burner End) conserves heat next to **R**, **Q** and **T**, and was ranked 4.0 on the Energy Scale. Loss of heat at **S** is essentially due to radiation. **P** (Exhaust End) conserves heat next to **S** and was ranked 3.0. At **P**, heat is lost mainly by convectional heat flow. The quantity of heat loss is substantial due to the high enthalpy of waste gases so that **P** jumped a step on the Energy Scale. This is due to the peculiar pattern of convectional heat flow in the crucible as against the rotary. During firing, the input heat is whirled all around the crucible pot within the hearth by the driving air-current thereby experiencing a circumferential circulation at the hearth before exiting through **P**.

2.1.3.2 Mode II: Production Operation

R (Furnace Body) conserves the most heat and was ranked 4.5 on the Energy Scale. **T** (Emergency Spout) conserves heat next to **R** and was ranked 4.0. In this operation, spills are envisaged and are, in fact, almost inevitable. A spill that is drained through **T** is tantamount to removal of heat energy from the furnace space.

S (Burner End) conserves heat next to **T** and was ranked 3.5 on the Energy Scale. **S** is an inlet opening that admits vaporized fuel into the combustion chamber. In practice however, the air-fuel volatile mixture produced by the burner is ignited at the mouth of the furnace so that some heat is lost by radiation from the open flames. **P** (Exhaust End) conserves heat next to **S** and was ranked 3.0. In Mode II operation, the enthalpy of the gasses in the furnace chamber is higher. The exhausts coming forth through **P** thus carry a substantial amount of heat so that the potential of **P** is less than that of **S**.

Q (Lid Opening) conserves heat next to **P** and, of course, least. It was ranked 2.0 on the scale. **Q** is an outlet opening subject to incessant opening for melt discharge (i.e. removal of crucible pot) and charging. Since the lid has the same diameter as the shell, on each opening of the lid, so much heat is lost by radiation and convectional flow that **Q** does not rank immediately after **P** but jumps a step on the Energy Scale.

A tabular summary of these analyses is provided in Tables 3 and 4.

2.2 Method II: Fuel Type and Fuel Combustion

2.2.1 Analysis of the Combusting Fuel

The following analysis holds for both furnaces since they both use diesel oil. Diesel is a distillate fuel oil of lower volatility and consists mainly of $C_{12}H_{26}$ to a composition of 98.5%; other constituents are 1% S, 0.25% N, and 0.25% O_2 [2]. Hydrocarbons undergo combustion according to the general equation:

$$C_xH_y + \left[x + \frac{y}{4}\right] O_2 \rightarrow [x] CO_2 + \left[\frac{y}{2}\right] H_2O \qquad (1)$$

Thus combustion equation for diesel is:

$$C_{12}H_{26} + 18.5\ O_2 \rightarrow 12CO_2 + 13\ H_2O \qquad (2)$$

In mass (kg) units

$$170\ C_{12}H_{26} + 592\ O_2 \rightarrow 528\ CO_2 + 234\ H_2O \qquad (3)$$

or

$$C_{12}H_{26} + 3.482\ O_2 \rightarrow 3.106\ O_2 + 1.377\ H_2O \qquad (4)$$

The waste gases are taken to be nitrogen from the supplied air, carbon dioxide and water. The percentage by volume of each is obtained to be 73.68%, 12.63% and 13.69% respectively. The mean specific heats are 1.3683 kJ/(m^3.°C), 2.1517 kJ/(m^3.°C) and 1.6601 kJ/(m^3.°C) respectively at an average temperature of

800°C from the Tables of Average Specific Heats of Air and Gases [1]. The average temperature of the waste gases exiting the furnace was taken as the average of the ambient temperature, 25°C, and the maximum temperature obtained from combustion of diesel in the rotary furnace, 1510°C [3]. Therefore, the mean specific heat of the waste gases, C_{wg}, is 1.5072 kJ/(m^3.°C. The calorific value of diesel is given as 45 357 kJ/kg [4].

2.2.2 Thermal Distribution of the Combustion Energy

Analysis of heat transfer in the combustion chamber of both furnaces would give the effectiveness of fuel combustion and the extent of heat lost to waste gases. From these, efficiency based on *fuel type and fuel combustion* can be calculated. These may then be compared with values obtained from *structure—operation* (section 2.1) estimations to arrive at a value representative of the general efficiency of both furnaces under actual conditions of production operation.

The various [3]heat items are computed below for the rotary and the crucible furnaces. According to Oyelami *et al.* [4] the total time of operation of each furnace comprises the time taken to preheat the furnace and the time taken to melt the charge. For both furnaces the preheating time was 50 min. The time of melt for the rotary was 90 min and the fuel flow rate (B_r) is 21.05 kg/h [5] while that of the crucible is 70 minutes with a fuel flow rate (B_c) of 17 kg/h. Thus, the total time of operation of the rotary (T_r) and the crucible (T_c) are 2.3 h and 2.0 h respectively.

The heat introduced into each of the furnaces was calculated from the chemical heat of fuel combustion, Q_1, given by (B_rQT_r) for the rotary furnace or (B_cQT_c) for the crucible furnace, where Q is the gross calorific value of fuel, 45 357 kJ/kg. The heat transported out of the furnace space are (i) the heat lost with the waste gases, Q_2, given by ($B_r\ V_{wg}\ C_{wg}\ t_a\ T_r$) where V_{wg} is the volume of waste gases produced from combustion, 12.329 m^3/kg of fuel; C_{wg} is the mean specific heat of waste gases at t_a, kJ/(m^3.°C); t_a is the average temperature of waste gases, 800°C. Note that B_r and T_r are for the rotary and are B_c and T_c for the crucible. (ii) Heat lost by conduction through the lining, Q_3, given by

[3]The formulae used here were adapted from Krivandin and Markov (1980).

$(T_r (t_1-t_0) / (S_r/K_r + S_s/K_s + 1/\alpha))$ where t_1 and t_o are the maximum (1510°C) and the initial (25°C) temperatures of the lining; S_r and S_s are the measured average thicknesses of the lining and the shell respectively, they are 0.110m and 0.005m respectively for the rotary and 0.200m and 0.005m respectively for the crucible; α is the coefficient of heat transfer from the lining to air, 19.8 W/(m^2.°C); K_r and K_s are respectively thermal conductivities of lining (1.37 W/(m.°C)) and steel shell (54 W/(m.°C)). [3,6]. And (iii) heat lost by radiation through the openings, Q4, given by $(C_o (T/100)^4 A \Phi T_r)$ where C_o is the emissivity of a black body, 5.768 W/(m^2.K^4) and Φ is the diaphragming coefficient, 0.7 [1]; A is the surface area, m^2 of the open doors (Exhaust/Charging end (0.06 m) and Burner end (0.05 m)) (obtained from measurement); T is the average temperature in the furnace space which is equivalent to t_a, (800°C or 1073K). Therefore, the useful heat available for the charge, Q_5, in each case is $(Q_1-(Q_2+Q_3+Q_4))$. The results of all these calculations are shown in Table 5.

3.0 RESULTS

The results are presented in Tables 3, 4 and 5.

In the rotary furnace, the various heat items have the following percentages; Q_1 (100%), Q_2 (33%), Q_3 (1.2%), Q_4 (0.11%), Q_5 (65.7%).

In the crucible furnace, the percentages of the various heat items are: Q1 (100%), Q2 (33%), Q3 (1%), Q4 (0.1%), Q5 (65.9%).

For both furnaces the efficiency based on *fuel type and fuel combustion* was calculated as the percentage heat conserved if the waste gases were considered as the *main source* of heat loss. The value is: (100 – 33) = 67% in the two cases. Other sources of heat loss are negligible and may not be regarded as having a significant effect on furnace efficiency.

4.0 DISCUSSION

Comparing the efficiency values obtained from the *fuel and fuel combustion* method (67%) with that obtained from *structure—operation* method in section 2.1 (Rotary: 74% Mode I and 72% Mode II; Crucible: 82% Mode I and 68% Mode II), the efficiency values for Mode II production operation are more comparable. For the crucible furnace Mode II efficiency is 68%. This value is very close to 67% obtained from *structure—operation*. Mode II efficiency for the rotary is 72% and it is considerably higher than 67%. It should be noted that the efficiency obtained from *fuel and fuel combustion* method was based on fuel combustion and heat lost with waste gases which did not take into consideration the rate of opening and closing of openings. From structural analysis and production operation however the rotary furnace has a better performance due to its ease of operation, homogeneity of melt, uniformity of firing and effective heat transfer to the charge. It can thus be concluded that 72% efficiency is more realistic for a rotary furnace.

Efficiency calculation based on *structure—operation* has the following features:

- Estimation of efficiency was based on average Energy Potential—a measure of capacity of energy points to conserve heat derived from observation of the production operation of both furnaces.
- The efficiencies are not the same for the two furnaces (unlike in the case of *fuel and fuel combustion*). This is due to the different designs and production operation of both furnaces.

Efficiency calculation based on *fuel and fuel combustion* has the following features:

- Estimation of efficiency was based on the heat lost with combustion products (waste gases mainly, being the major source of heat loss).
- The efficiency is the same since both furnaces use diesel and the fundamental mechanism of combustion is the same.
- Heat carried away with waste gases was used with no consideration for the rate of loss and degree of exposure of the combustion chamber.

5.0 CONCLUSION

Mode II production operation is the closest to the general industrial operation of both rotary and crucible furnaces encountered in real life productions. The efficiencies of the crucible and rotary furnaces based on *structure—operation* are 68% and 72% respectively. The general industrial operation of both furnaces should be regarded as close to Mode II operation. The efficiency for both furnaces based on *fuel type and fuel combustion* is 67%. Both furnaces have the same efficiency when the same type of fuel (diesel) is used since the fundamental mechanism of fuel combustion is the same in both furnaces.

In both methods, the efficiencies obtained are quite comparable in the case of the crucible, whereas for the rotary they are not. Considering the production operation of both furnaces, the rotary is generally assessed to be more efficient than the crucible in terms of ease of operation, homogeneity of the melt, uniformity of firing and effective transfer of heat to the charge. Therefore the efficiency of the rotary furnace obtained from *structure—operation* (72%) is more realistic. The fuel type is a factor which may affect efficiency of both furnaces. This is because parameters such as amount of heat generated and impurity (type and quantity) that will be present in the melt are determined by the fuel. The more the heat generated the better the efficiency and the less the impurity the better the efficiency.

Efficiency values obtained from Structure—Operation (Mode II) is recommended for the functional assessment of both furnaces. This is because this approach takes into consideration the structure, modes of production operation, and the capacity of the openings for conserving heat energy during each mode of operation. This approach thus provides the efficiency from factors which are peculiar to each furnace.

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Table 1: Designation and Function of Energy Points in a Rotary Furnace

Energy Points	Description	Function/purpose
A	Burner end	Inlet opening for admitting heat energy into the furnace space through firing
B	Pouring spout	Outlet opening for pouring molten metal from the furnace space into moulds
C	Emergency spout	Outlet opening serving as an alternative pouring spout if blockage occurs
D	Exhaust/Charging end	Outlet opening for combustion products./ Introduction of charge into the furnace space.
E	Furnace body	Outlet opening inadvertently incorporated in the furnace structure

Table 2: **Designation and Function of Energy Points in a Crucible Furnace**

Energy Points	Description	Function/Purpose
P	Exhaust end	Outlet opening for combustion products.
Q	Lid opening	Introduction of charge into the furnace space and removal of crucible pot from the furnace
R	Furnace body	Outlet opening inadvertently incorporated in the furnace structure
S	Burner end	Inlet opening for admitting heat energy into the furnace space around the crucible pot
T	Emergency spout	Outlet opening serving as an emergency exit if a *spill occurs

*Occasionally a spill of molten metal may occur in the hearth (i.e. the furnace bed); the Emergency Spout helps to drain it out in order to prevent a crack either in the refractory lining or crucible pot.

Table 3: Average Potential and Efficiency for Rotary Furnace

Mode I		Mode II	
Energy Point	Energy Potential	Energy Point	Energy Potential
E	4.5	E	4.5
C	4.0	A	4.0
B	4.0	C	3.5
A	3.5	B	3.5
D	2.5	D	2.5
Overall potential	18.5		18
Average Potential	3.7		3.6
Efficiency	74%		72%

Table 4: Average Potential and Efficiency for Crucible Furnace

Mode I		Mode II	
Energy Point	Energy Potential	Energy Point	Energy Potential
R	4.5	R	4.5
Q	4.5	T	4.0
T	4.5	S	3.5
S	4.0	P	3.0
P	3.0	Q	2.0
Overall potential	20.5		17
Average Potential	4.1		3.4
Efficiency	82%		68%

Table 5: Analysis of Heat Transfer in the Combustion Chambers of the Furnaces (as calculated in section 2.2.2)

	Rotary Furnace	Crucible Furnace
Q_1 (kJ)	2 195 959	1 542 138
Q_2 (kJ)	719 728	505 438
Q_3 (kJ)	26 095	15 108
Q_4 (kJ)	2 360	1 478
Q_5 (kJ)	1 447 776	1 020 114

Q_1 – Chemical heat of fuel combustion

Q_2 – Heat lost with waste gases

Q_3 – Heat lost by conduction through the lining

Q_4 – Heat lost by radiation through the openings

$_5$ – Useful heat available for the charge

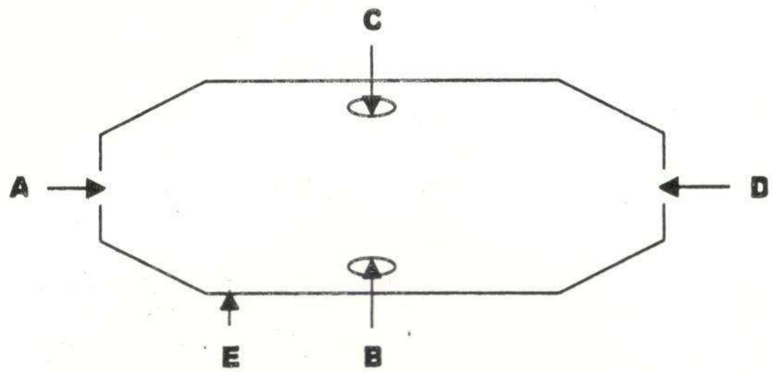

Figure 1: Position of Energy Points in a Rotary Furnace. (See Table 1 for explanations).

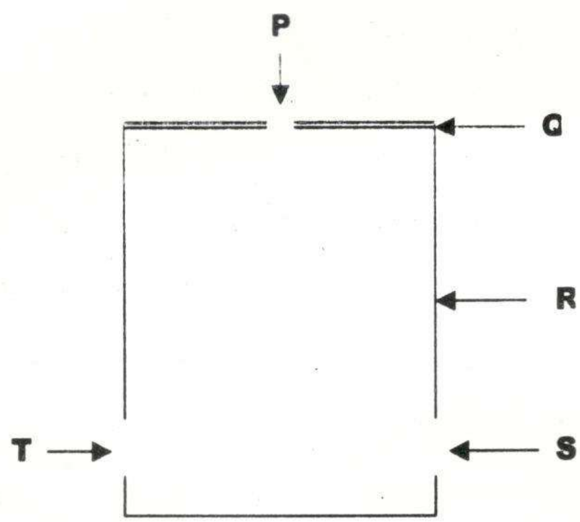

Figure 2: Position of Energy Points in a Crucible Furnace. (See Table 2 for explanations).