STUDY ON HIGH TEMPERATURE GAS-FIRED CRUCIBLE FURNACE

By

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A thesis submitted to the Department of Metallurgical Engineering, BUET, Dacca in partial fulfilment of the requirements for the Degree of Master of Science in Engineering (Metallurgical).

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CERTIFICATE

This is to certify that this research work was done by the author under the supervision of Dr.M.Ibrahim, Professor and Ex-Head, Department of Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dacca and it has not been submitted elsewhere for the award of any other degree or diploma.

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The undersigned examiners appointed by the Committee of Advanced Studies and Research(CASR) hereby recommend the acceptance of the thesis "STUDY ON HIGH TEMPERATURE GAS-FIRED CRUCIBLE FURNACE", submitted by Md.Nasrul Haque, B.Sc.Engg.(Met.) to the Department of Metallurgical Engineering, BUET, Dacca in partial fulfilment of the requirements for the Degree of Master of Science in Engineering (Metallurgical).

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ABSTRACT

For small scale ferrous/nonferrous melting crucibles are generally used in the foundry, which are very costly and sometimes difficult to procure. An attempt has, therefore, been made in the Metallurgical Engineering Department of the BUET to melt cast iron/pig iron in a melting furnace without the conventional crucibles. The furnace hearth itself has been used as a container for the molten metal.

With this furnace it has been possible to attain maximum temperatures in the range of 1380-1410°C and to melt about 70 lbs. of solid pig in about 25-35 minutes. The charging-to-tapping time for the first heat has been observed to be a maximum where the charge and the furnace linings are cold, and this gradually decreases to a minimum value within a few subsequent heats.

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CHAPTER 1 : INTRODUCTION

Metal casting is an old traditional art. Primitive man of stone age aquired some knowledge of melting metal even before 3500 B.C(1). In the history of metal it is accepted that the campfire was the oldest traditional melting process. The idea of melting metal in a container was not known to the earlier man. In the campfire metals were melted and found scattered within the ashes. He then made a hole within the fuel and put some container and got the metal melted in it. It was then only possible to get the low melting point metal in a molten condition. The wall of the hole was strengthened by high temperature resistant stone so that the burning flame might not be acattered and got concentrated in the stone-walled campfire or furnace. Thus the technique of pit furnace or crucible furnace was developed. This was only possible when smaller quantity of molten metal was needed. Later on when large quantity of molten metal was wanted the idea of hearth furnace, arc furnace and cupola furnace were eventually developed.

At present, when cupola furnace, air furnace or arc furnace is used no specific container is required. For small scale melting, graphite, plumbago and other different types of ceramic crucibles are generally used. The heating in most cases is done by coal, coke, oil or gas. However melting metal by gas, though much cheaper, is not yet much in use in this country.

Crucibles are imported from abroad and recently it is reported that these crucibles are very costly and beyond the capacity of most foundrymen to procure them from abroad. For this reason a U.G.C. project was carried out in the Met.Engg. Dept. of the BUET to melt metal in furnace without using either any crucible or coke. It is known that low melting metals and alloys having melting points upto around 1100°C can easily be melted in this type of furnace(2).

To melt ferrous materials having higher melting points using furnace bottom as a crucible, it is necessary to develop high flame temperature at the furnace bottom. This project, "Study on high temperature gas-fired crucible furnace", has been undertaken to design a crucible furnace to melt cast iron, which requires temperatures between 1250-1350°C.

If this can be established that cast iron melting is possible in a furnace where the furnace bottom itself is acting as crucible, then this will save the foundrymen from the botheration of procuring the costly crucibles.

CHAPTER 2 : LITERATURE REVIEW

To design a gas-fired crucible furnace a working knowledge about the furnace, its fuel(natural gas in this case), aerodynamics, heat-transfer and refractories will be necessary. This chapter deals with the relevant informations needed in the design of furnace. The informations are divided into the following five sections :

Types of furnaces
Types of fuel for heat generation
Transmission of heat to the charge/surrounding
Furnace aerodynamics
Refractories

2.1 Types of furnaces

Types of furnaces used for melting ferrous and nonferrous metals are :

1. Crucible Furnaces
2. Cupola Furnaces
3. Air Furnaces
4. Open hearth Furnaces
5. Electric Furnaces, etc.

Crucible furnaces are used in foundries for melting small quantities of ferrous and nonferrous metals. The charge is melted in a refractory pot which is usually fired externally by coal, coke, gas or oil. Alternately, the crucible may be an integral part of an induction furnace. The charge is generally isolated from the furnace gases in most cases. Figure 1 . shows the range of improvements of primitive pot fired furnaces with gradual control over combustion. In oil-fired or gas-fired crucible furnaces, the use of correct rate of fuel consumption and fuel-air ratio are of prime importance. Fuel is wasted if either too much or too little fuel or air is used. The optimum conditions are indicated from the shape and colour of the exhaust flame.

The size of crucible, shape, dimensions of the combustion chamber and off-take flues are primarily matters of initial design. During operation worn lining of the furnace should be constantly kept in repair.

In most of the melting furnaces, heat is generated by combustion of fuel with supply of oxygen through air, excepting thermoelectric furnaces where heat is developed by the application of electricity. The furnace that has been used in this project is also a combustion furnace using gaseous fuel. Natural gas is burnt with air for melting purposes. In this design importance is given for the transfer of heat from the combustion product into the charge so that molten metal with sufficient fluidity be obtained in a reasonable quantity for casting purposes.

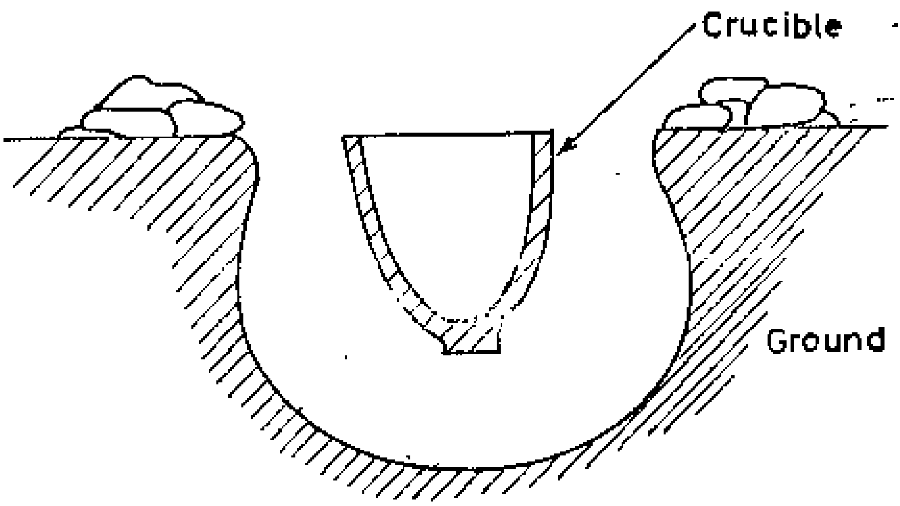


Fig. 1a. A "Camp – fire" with the centre sunk to hold a crucible (3).

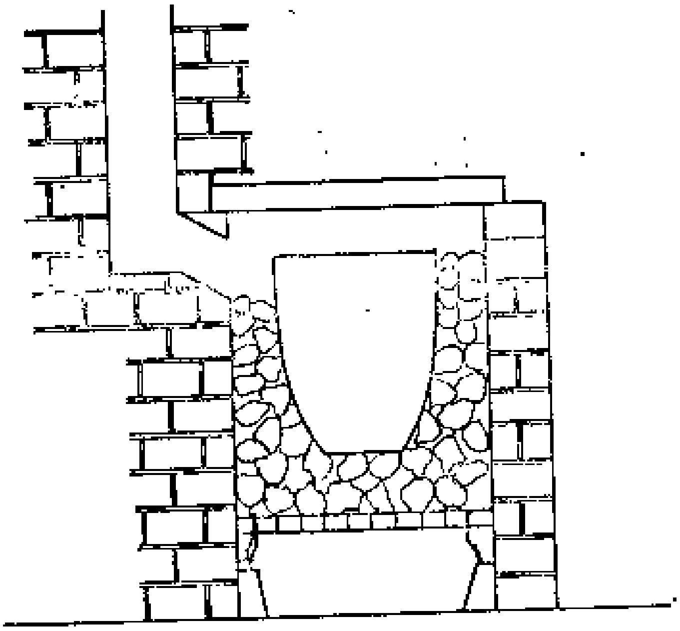


Fig. 1b. Simple, natural draught, coke fired, pit type crucible furnace (4)

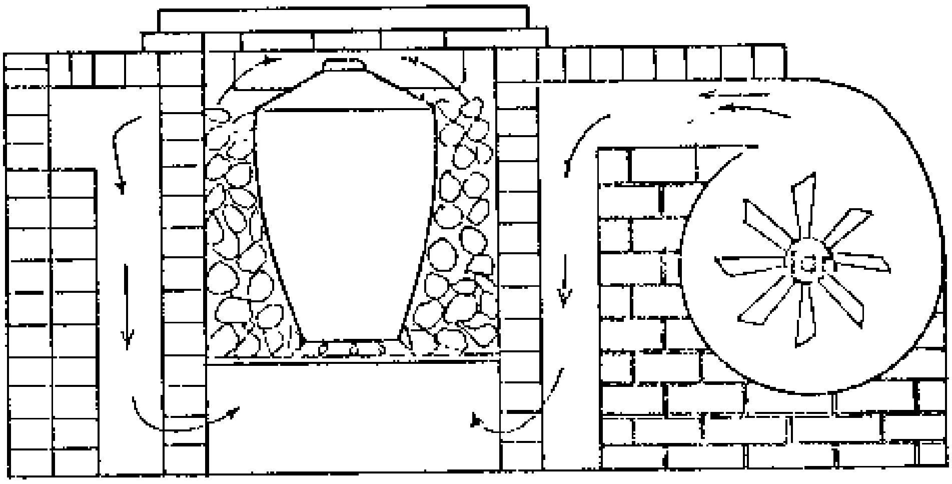


Fig. 1c. Forced draught permitting some preheating of the air and better control over combustion rate (4).

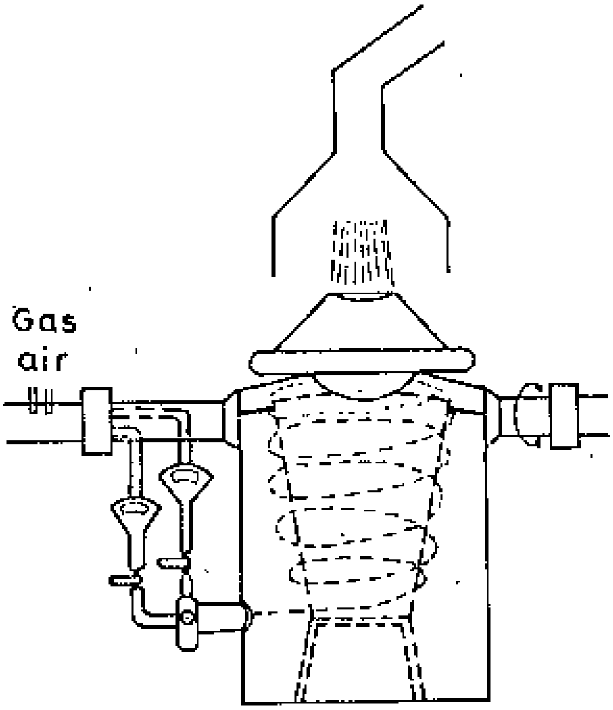


Fig. 1d. The use of gas or oil firing allows tilting crucible furnace to be developed with better/rapid control over combustion rate (4).

2.2 Fuels for heat generation

Fuels may be classified as :

Solid e.g. wood, coal, coke, etc.

Liquid e.g. petroleum, coal-tar, etc.

Gaseous e.g. natural gas, coal gas, producer gas, etc.

The chief fuel available in Bangladesh is natural gas. The basic property of a fuel is its calorific value. The calorific value of naturally occuring gaseous fuel is much more than other types and also the gaseous fuel has some advantages over the other types. These are briefly as follows (5) :

a) Smoke and ash are eliminated and there is no labour involved in fuel or ash handling.

b) The combustion may be readily controlled for changes to meet the demand of oxidizing or reducing nature of atmosphere, the length of the flame and the temperature.

c) Greater thermal efficiency can usually be obtained when high temperatures are required.

Table 1 shows the chemical composition and calorific values of natural gas available in Bangladesh (6).

Table 1

Place	Composition (vol%)						Calorific value(gros (Btu/ft^3)
	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2	
Titas	96.9	1.8	0.5	0.2	0.3	0.3	1036
Chhatak	99.05	0.24	-	-	0.67	0.04	1007
Sylhet	95.4	2.67	0.3	0.78	0.37	0.48	1052
Habigonj	97.8	1.5	-	-	0.7	-	1020
Bakhrabad	94.3	3.4	0.8	0.6	0.4	0.5	1022
Kailas Tila	95.7	2.6	0.9	0.4	0.2	0.2	1030
Rashidpur	98.20	1.20	0.80	0.10	0.25	0.05	1014

It can be seen from the above table that the predominant fuel components are the saturated hydrocarbons CH_4, C_2H_6, C_3H_8, C_4H_{10} and the non-combustibles are N_2 and CO_2. The main component of natural gas is CH_4. Other hydrocarbons do not exceed 4.8% by volume. H.L. Wu and J.Jasiewicz(7a) found that the higher hydrocarbons C_2H_6, C_3H_8 and C_4H_{10} have combustion qualities superior to those of CH_4, and that they improve flame stability when present in natural gas.

2.3 Transmission of heat to the charge/surroundings

Ignition and combustion of fuels in a furnace, development of heat, attainment of furnace temperature and finally the absorption of heat by the charge depend on the laws of heat transfer. Thus a study of the principles and laws governing transfer of heat is essential for designing any furnace.

The liberation of heat energy is only the first stage in the heating operation. This energy has to be transfered to the charge to be melted as completely as possible and its dissipation to the surrounding reduced to a minimum.

2.3.1 Radiation of heat by gases

In this design hot flue from the combustion chamber will enter the furnace and transmit heat to the charge and the furnace wall by means of radiation and convection before it leaves the furnace through an exhaust port. Carbon dioxide, water vapour and hydrocarbons are good radiating gases whereas carbon monoxide is a relatively poor radiator of heat. For most practical purposes hydrogen, oxygen and nitrogen are non-radiators (8). The radiation effect of a nonluminous flame is accordingly governed mainly by its carbon dioxide and water vapour contents. According to Reich (9) the quantity of heat, radiated by CO_2 and H_2O vapour are as follows :

$$Q_{CO_2} = \left(0.019 - \frac{0.00019}{P_cL + 0.01}\right)(t_g - 200)^2 \text{ Kcal/m}^2\text{-hr.}$$

$$Q_{H_2O} = \left(0.095 - \frac{0.01615}{P_wL + 0.17}\right)(t_g - 200)^2 \text{ Kcal/m}^2\text{-hr.}$$

Where

P_c = partial pressure of CO_2

P_w = Partial pressure of H_2O vapour

L = Effective thickness of gas layer, which is found from the emperical expression :

$$L = \frac{\text{vol. of gas space X 3.4}}{\text{area of boundinding wall}}$$

t_g = temperature of the gas

The total quantity of heat radiated,

$$Q = Q_{CO_2} + Q_{H_2O} = (0.114 - \frac{0.00019}{P_c L + 0.01} - \frac{0.01615}{P_w L + 0.17}) (t_g - 200)^2 \text{ Kcal/m}^2\text{-hr.}$$

If t_1 be the temperature of the absorbing body, then

$$Q = (0.114 - \frac{0.00019}{P_c L + 0.01} - \frac{0.01615}{P_w L + 0.17}) (t_g - 200)^2 - (t_1 - 200)^2 \text{ Kcal/m}^2\text{-hr.}$$

2.3.2 Radiation of heat from the surface of the furnace

Stefan (10) found experimentally that the total radiant energy emitted by a hot body varied as the fourth power of the absolute temperature of the body. In the case of a black body at an absolute temperature T the amount of heat radiated per unit area is given by Stefan's law as $q = \sigma T^4$

the coefficent σ has the value

1.73×10^{-9} Btu/sq ft-hr $(^{\circ}R)^4$

For convenience of calculation the above equation can be written as $q = 0.173 \left(\frac{T}{100}\right)^4$ Btu/sq ft -hr.

The total radiation from a non-black body having an emissivity e will be $\sigma e. T^4$.

The above equation expresses the heat which a solid body emits by radiation; it does not express the heat transferred to the surroundings. The heat actually transferred is the difference between emitted heat and heat received by radiation from the surroundings. This difference equals

$$Q = 0.173\ A\ .\ e\ .\ (\frac{T_o}{100})^4 - (\frac{T_a}{100})^4$$

Where A = area of the radiating surface, Btu/hr.

e = net emissivity

T_o and T_a = absolute temperatures of the radiating surface and the surroundings respectively.

2.3.3 Radiation of heat through openings

Fig.2 indicates a furnace in which there is a hole in the furnace wall. An observer at A would see the interior of the furnace as if that interior were a plane surface situated at the opening and having the same area as the opening.

Since the radiation from the interior of a furnace is generally taken to be equivalent to black-body radiation(e=1) the rate of heat radiation per unit area of plane surface observed would be given by Fig.3 (using radiation equation) for a furnace having walls of negligible thickness at the opening.

The finite thickness of the wall, however, changes matters. It obstructs the direct ratiation to an extent depanding on the

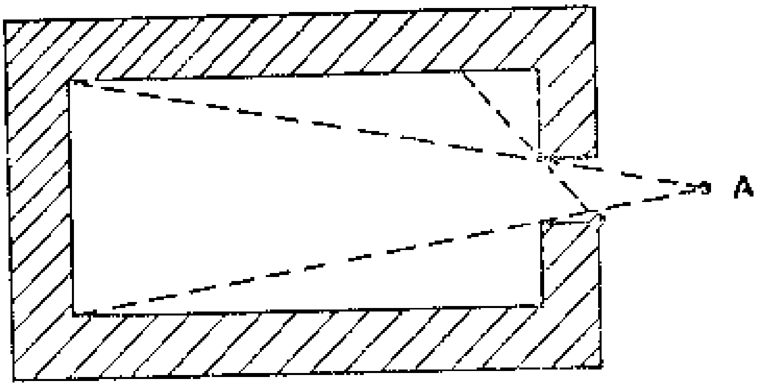


Fig. 2 Diagrammatic illustration of heat radiation from an opening in a furnace

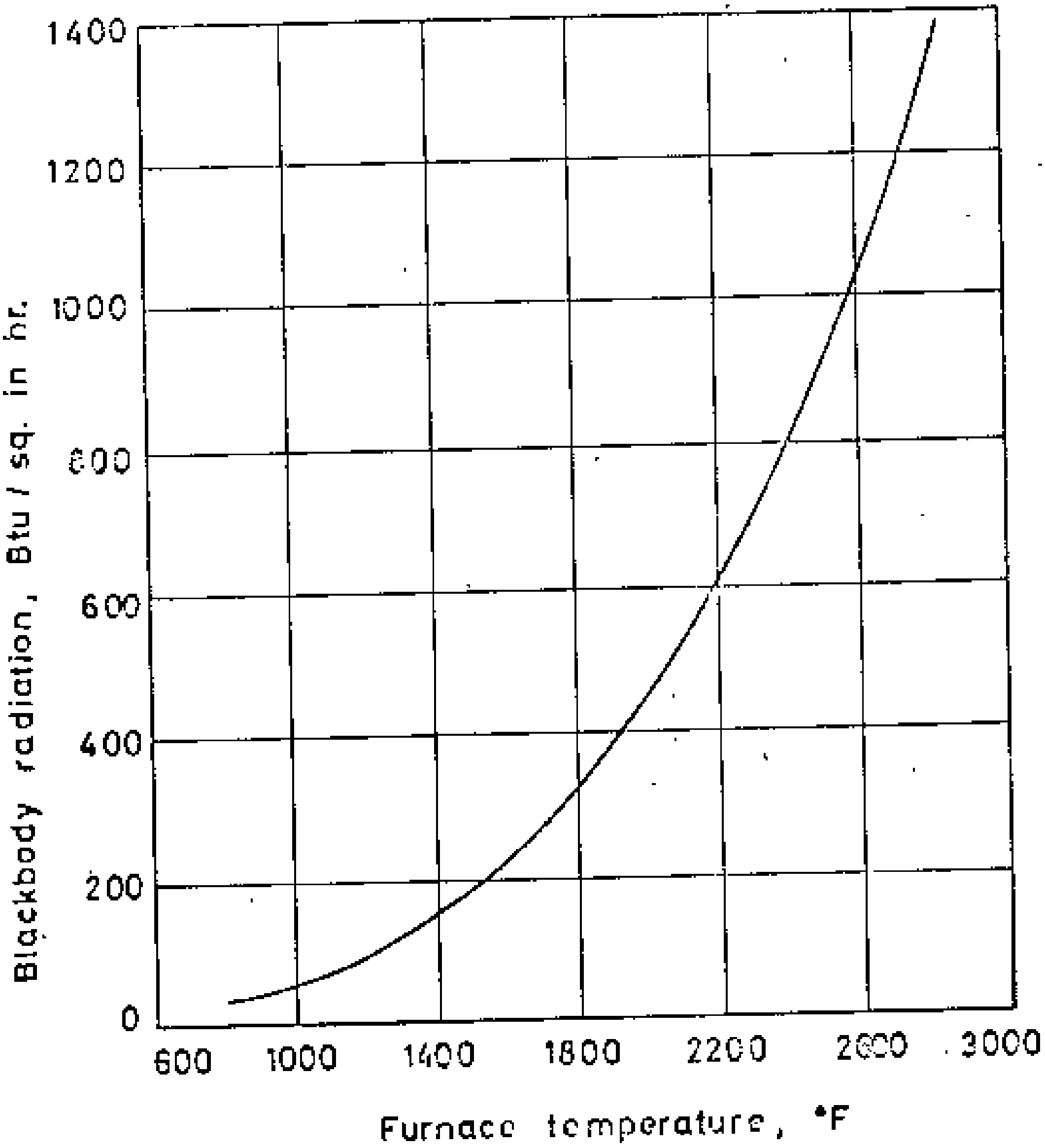


Fig. 3 Blackbody radiation from a furnace interior.

ratio of the wall thickness to the width of the opening. On the other hand, the sides of the opening become heated by the radiation that they receive and re-radiate a portion of this heat to the outside. The re-radiation partially compensates for the reduction of direct radiation. The ratios of total radiation to the direct radiation for openings of various shapes obtained by Koller (11) are given in Fig.4.

2.3.4 Transfer of heat from the surface of the furnace by natural convection

The transfer of heat by natural convection is governed by the area of the surface, the shape and position of the surface and the temperature difference between the surface and the air. A useful empirical expression (8) for the rate of heat transfer, H_c, is $Hc = C(t_o - t_a)^{1.25}$ Btu/ft^2-hr.

where t_o and t_a = temperatures of the surfaces and the surrounding air respectively.

C = constant depending on the shape and position of the surface.

The value of C as determined by experiment is as follows (8):

C = 0.39 for a place horizontal surface facing up and hotter than the surrounding air.

C = 0.3 for plane vertical surfaces and for large bodies of irregualr shape but without re-entrant angles.

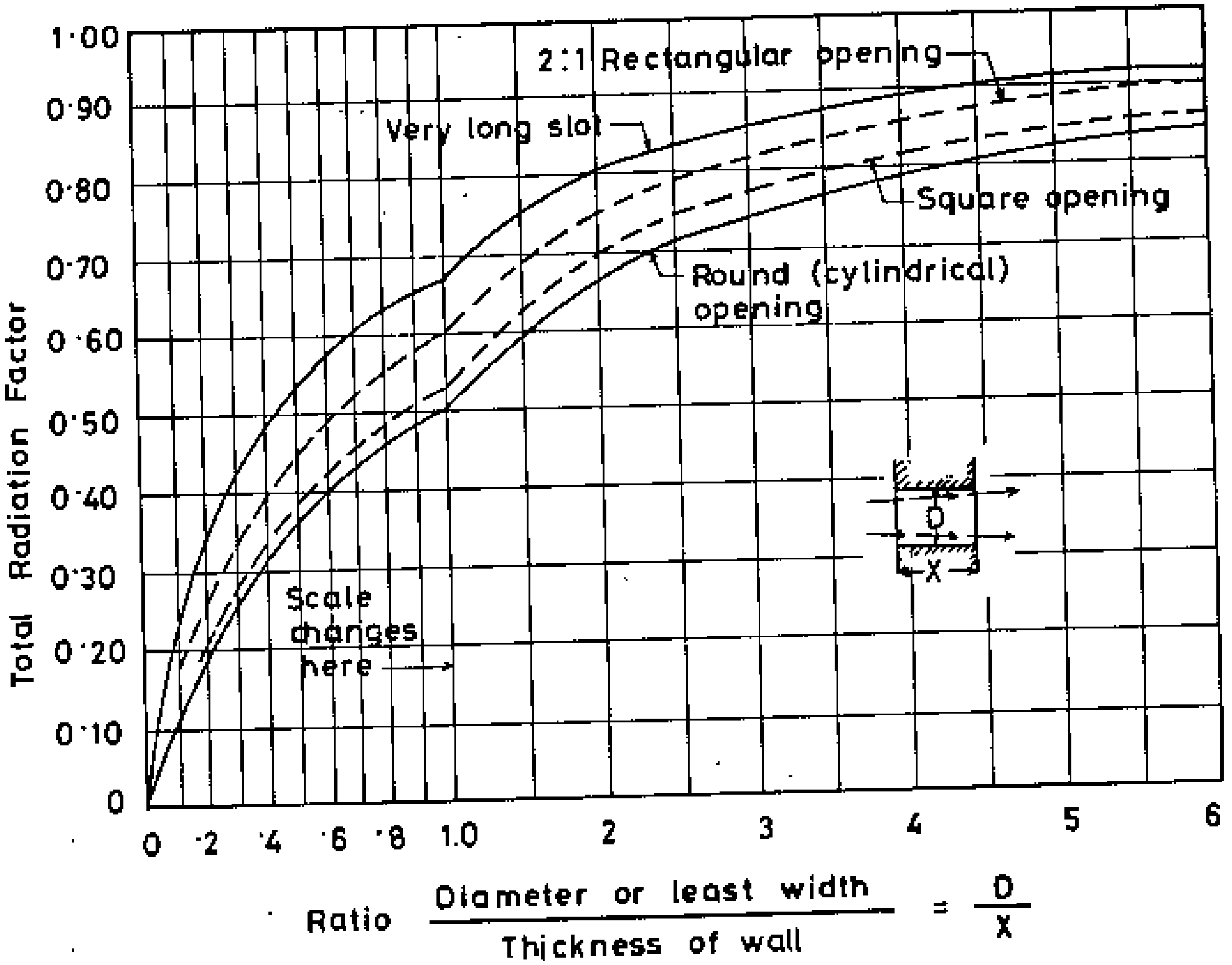


Fig. 4 Radiation through openings of various shapes(11).

C = 0.2 for horizontal surfaces facing downwards and hotter than the surrounding air.

C = 0.35 for large horizontal cylinders(and this applies to pipes) over 6 inches diameter.

2.3.5 Sensible heat carried out of the furnace by products of combustion.

In combustion-type furnaces, the products of combustion take out heat energy either in potential from in the shape of unburned fuel or in kinetic form in the shape of sensible heat. The sensible heat of hot gases can be calculated from the quantity of these gases, their temperatures and their respective specific heats. Alternatively, the Rosin-Fehling I.T diagrams, Fig.5 may be used to obtain sensible heat (10).

2.4 Furnace aerodynamics

Gas flow in furnaces is almost entirely turbulant. This flow may be either steady or eddying. In steady flow there is a narrow layer of laminar (streamlined) flow along the boundary surface in which the velocity rises from zero at the boundary to the bulk velocity in very short distance. At bends, or at changes in cross-section, unless these are very gently, this laminar layer breaks away from the surface and an unstable condition ensures in which "eddys" break off the gas body and move into the "space" formed between the gas body and the surface. The formation of eddys dissipates a lot of energy as heat and

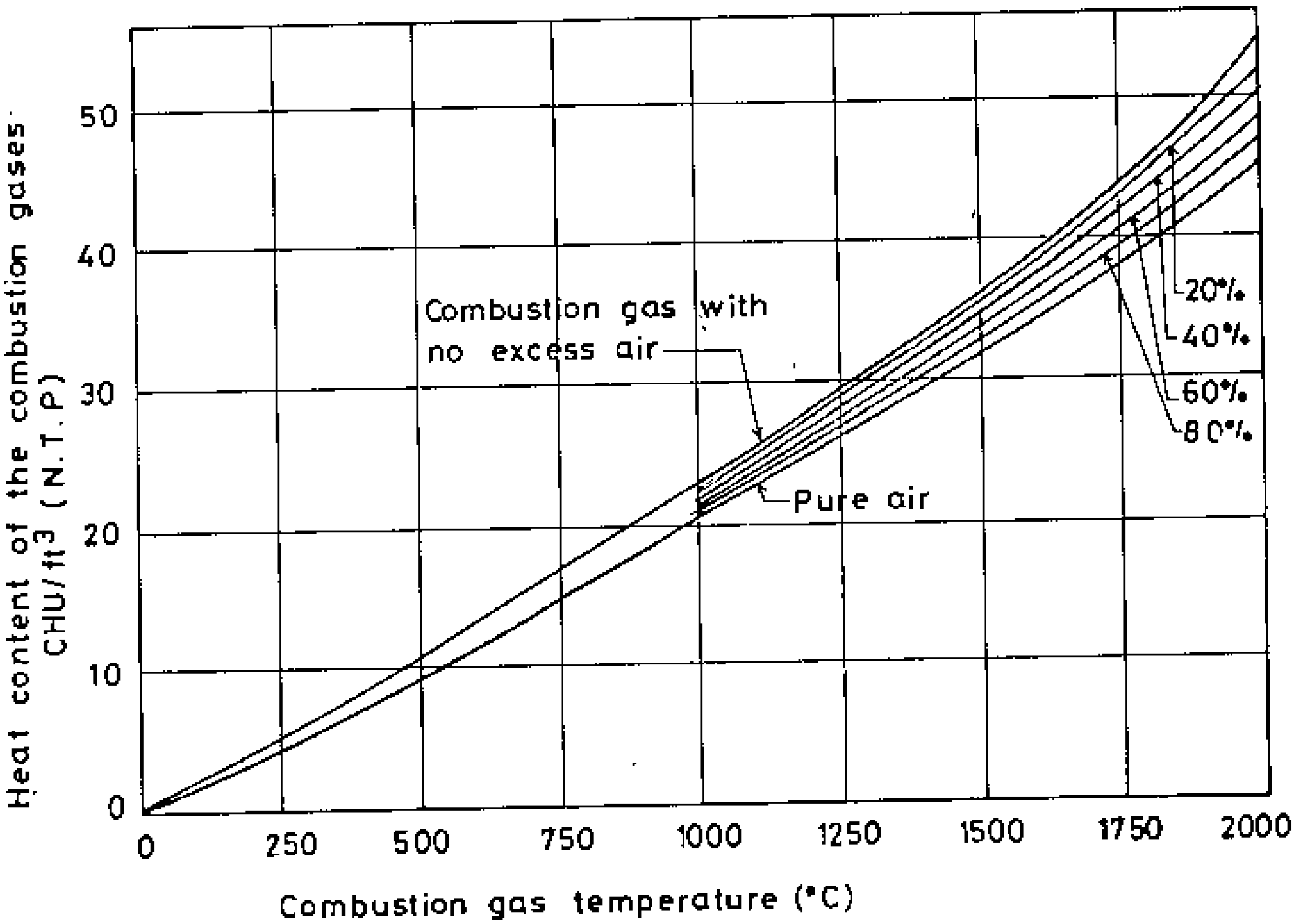


Fig. 5 Rosin – Fehling I. T. diagram relating the heat content of combustion gases from all normal fuels burnt with air to their temperature. (10).

Figures attached to the intermediate curves denote the percentage of air in the mixture of combustion gas and air.

sound results in a severe loss of pressure.

The force P, driving gases through a furnace system is the algebraic sum of initial pressure, P_o, the net pressures due to the various bouyancy effects, $\sum(\Delta P_b)$, the pressures developed by any fan or blower, $\sum(\dot{\Delta} P_f)$ and the pressure losses due to frictional resistance to flow, $\sum(\Delta P_r)$. This might be written as:

$$P = P_o + \sum(\Delta P_b) + \sum(\Delta P_f) + \sum(\Delta P_r).$$

P_o can usually be ignored as it is normally the atmospheric pressure against which the others are measured but if only part of a system were under consideration it might have to be included in the calculation.

ΔP_b is due to the difference between the weight of the hot gas in the shaft and that of a column of cold air of the same height and cross-sectional area outside. This is given by

$$\Delta P_b = (\rho_a - \rho_g)h$$

Where ρ_a = density of surrounding atmospheric air; ρ_g = density of gas flowing; h = height of the shaft.

Both ρ_a and ρ_g are measured at their respective temperatures and pressures, with due regard to the presence of any water vapour. A mean value of the different pressures and temperatures is normally used.

Fans, blowers, etc. may be used to accelarate the gas flow either supplementing the natural draught or replacing it altogether. The aeromotive force of the fan or blower in pressure units is added to the net bouyancy to give the total positive force driving the gases through the systen.

There is pressure drop due to friction at all points in a furnace systen, lest in long wide straight flues, and greatest at sharp bends, sudden changes in section, junctions and baffles. Pressure drop due to changes in section, and eddying at bends is given by

$$-\Delta P_r = \frac{S' X \rho_g u^2}{2g} \text{ lb/ft}^2 \text{ or kg/m}^2$$

Where ρ_g and u are the density and the velocity of the gases respectively and measured at the mean temperature and pressure of the gases flowing in the furnace. S' is a factor allowing for losses due to eddying at bends and changes of section. Values of S' for furnaces have been calculated and a comprehensive table is given elsewhere(8).

In straight sections the pressure loss is due to friction at the walls and is affected by the texture of their surfaces. In straight round sections the loss of pressure is given by

$$-\Delta P_r = \frac{\rho_g u^2}{2g} . \frac{L}{D} . F$$

Where L and D are the length and diameter of the(circular) section, F is the friction factor which depends on the Reynolds number and the roughness of the boundaries. If the section is not cricular D may be replaced by 4M, where M is the "mean hydraulic depth" of the section and is given by

$$M = \frac{\text{cross-sectional area}}{\text{wetted perimeter}}$$

The first essential prerequisite in furnace design is that heat shall be developed at a required rate. This necessitates the combustion of a certain amount of fuel and so the design must be such that the fuel and air can reach the combustion chamber and the products of reaction escape from it at an appropriate rate and without unduly high pressures being necessary. Resistance to flow should therefore be as small as practicable except where some advantage is to be gained.

In any deep section of the furnace, pressure differentials may develop normal to the flow direction, due to bouyancy. Further, distinct stratification of hot and cold gas can also occur, and in spite of turbulent flow conditions these may be present. The obvious case is where there is cold stock on the hearth. This cools the gases that come low over the hearth and these, having become relatively dense, fail to mix with the hot light gas in the roof. This is wasteful as available heat is denied access to the stock, and furnace design should attempt to minimize such an effect for example by making the hearth wide and the roof low or by deflecting the burned or burning gases downwards on to the hearth (4)

2.5 Refractories

Refractory materials have long been accepted as indispensable to high-temperature technology in providing the lining for furnace enclosers in which such reactions as involved in the manufacture of iron, steel, glass, etc. can be carried out effectively, safely and economically.

A refractory material in its working environment has to withstand high temperatures without undergoing major structural changes including chemical decomposition and must provide resistance to attack by gases, liquids, or solids in contact with the refractory. The refractory must have sufficient strength at high temperature to support the refractory structure and to withstand the induced or applied stresses.

There are a large number of chemical substances with high melting points, such as oxides, carbides, silicides, nitrides, berryllides, sulphides, borides and certain elements (e.g. carbon and some metals) and hence all may be considered as potential refractory materials (7b&c).

The large majority of the materials with the exception of certain oxides, have no commercial importance because of their scarcity or cost or lack of chemical stability. Two nonoxide exceptions are silicon carbide and elemental carbon which are extremely useful refractory materials for certain furnace work, carbon playing an important but restricted part under reducing conditions as in blast furnace.

Reference to any comprehensive inorganic text book shows that there are at least 20 oxides with melting points over

1700°C but the majority of these oxides, like most of the above mentioned special ceramic materials, are scarce, have a high cost, or are unsuitable in various atmospheres. It therefore, seems inevitable that refractories will continue to be based on the six oxides Al_2O_3, SiO_2, MgO, CaO, Cr_2O_3 and ZrO_2 in either a single or a multiple component combination of these oxides.

According to Dixon (12) refractories may be classified as follows :

"Acid"group consisting of silica and semisilica

"Basic" group, consisting of magnesite, chrome, dolomite and forsterite.

"Alumino-silicate" group, consisting of fireclay and the high alumina grades based on kyanite, sillimanite, andalusite and bauxite.

"Sundries" group, which includes carbon, plumbago, silicon carbide, fused alumina, Zircon, pure oxides and cermets.

The most widely used refractories are the "alumino-silicate" group. The maximum working face temperature of these materials is generally in the 1400 to 1500°C range. They offer the advantages of low thermal conductivity (the lowest of any known refractory), very low bulk density and excellent chemical resistance.

Pure Al_2O_3(2020°C) and pure silica (1723°C) are materials of intrinsically high melting point but as soon as silica is admixed with alumina, and alumina with silica, the melting temperatures are depressed. Melting starts at 1840°C and 1590°C respectively for alumina-rich and silica-rich compositions(Fig.6). Above these temperatures a solid may co-exist with the liquid. Below these particular temperatures the compositions are wholly solid, consisting of two crystalline phases as shown, except for the narrow region in which mullite alone appears.

This diagram illustrates how reaction between two refractory oxides produces lower-melting liquid phases. It also shows that with alumina above 5%, the refractory properties of Al_2O_3 - SiO_2 mixtures increase directly with the content of Al_2O_3. The general properties of commercial refractories of this type are shown in table-2 .

This shows that actual alumino-silicate refractories may depart markedly from the equilibrium composition. The raw materials and finished products contain impurities which can lower the melting point of the liquid phase.

The life of a refractory lining for a high temperature furnace depends not only on its physical and chemical quality and its working temperature but also on the nature of the working environment, which is generally the main factor that has to be considered in selection of a refractory. The working environment is the main cause of wear and subsequent failure of refractory. Refractory linings for tunnel kilns, where there is

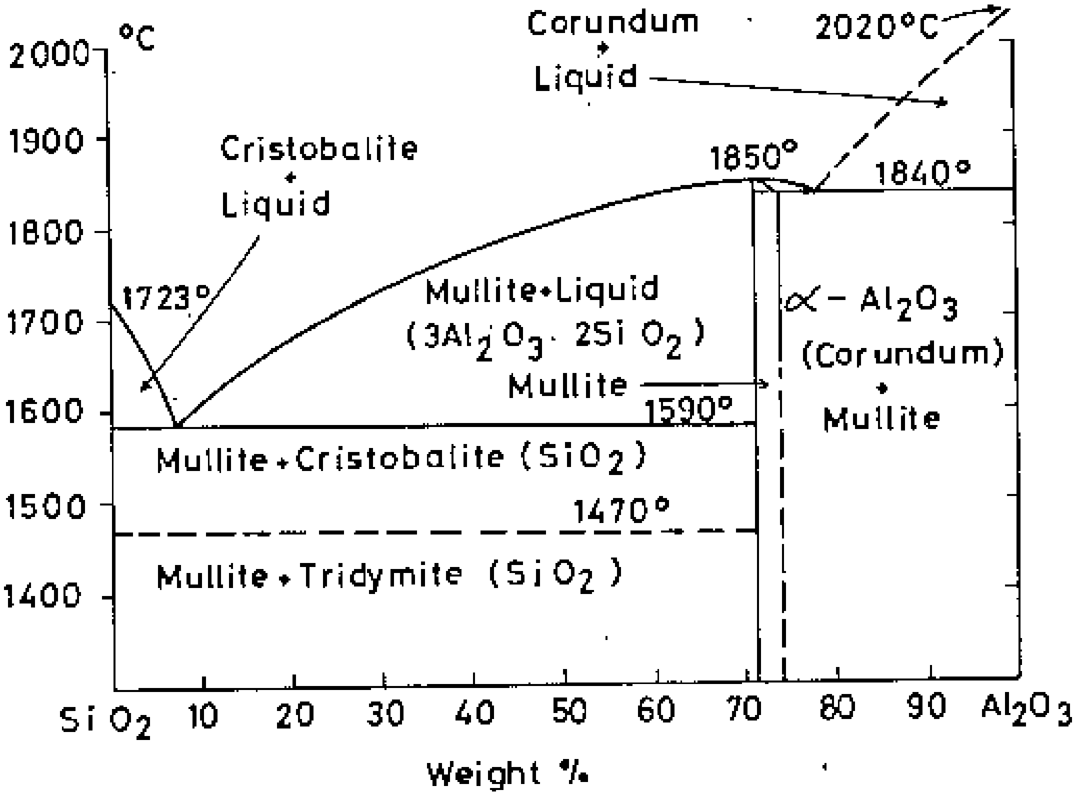


Fig. 6 Phase diagram for the system $Al_2O_3-SiO_2$, based mainly on the work of Bowen and Grieg (1924), but including more recent modifications (7).

TABLE 2 The alumino-silicate range of refractories (fire-bricks); broad relationships between composition and properties (7)

	$\%Al_2O_3$	$\%SiO_2$	Raw material	Refractoriness (^oC)	Approx. safe temperature of use (^oC)	Properties and principal applications
Group I	20 30 37 42	70 60 56 52	Fireclays: mixtures of clay mineral, quartz and mica; plus impurities such as Fe_2O_3 1-1.5% TiO_2 1.4-3.4% Alkalis 0.5-1.5%; Cao, MgO <1% of each	1610 1690 1720 1740	1200 1350 1400 1450	In all heat using industries; type chosen according to conditions; the largest tonnage refractory
Group II	55 60 66	43 38 32	Natural alumino-silicates (kyanite, sillimanite, andalusite) approximating to $Al_2O_3.SiO_2$. Fe_2O_3 1-1.5; other impurities low, totalling 1-1.6%	1780 1810 1830	1500 1600 1600	Good high-temperature properties, especially creep resistance endowed by mullite formation and favourable micro structure. Usually good resistance to alkali attack. Glass-tank superstructure and checker; combustion chambers; rotary kilns, open hearth checkers, hotblast stoves.
Group III	80-85	9-12	Bauxite based	1850	1650	Furnace hearths, hot-metal mixers, soaking pits, lime kilns.
Group IV	86	9-12	Al_2O_3 with mullite bond	–	1650	High cost materials on volume basis; for severe operating conditions where cost is justified by life.

no severe chemical attack, will last in excess of 5 years without repair with the operating temperatures as high as 1750°C. This can be compared with refractory linings for certain steel making furnaces, operating at 1600°C to 1700°C maximum temperature where the lining is exposed to severe chemical attack and the lining has to be replaced often after only 2 weeks in service(7c).

The refractory used in this investigation is high alumina brick and high alumina fireclay procured from M/S.Dacca Refractory Ltd. Although Table-3 below shows that the thermal conductivity and bulk density of fireclay brick are lower than those of high alumina brick (7d), the former cannot be used as facing brick in furnaces where the working temperature is above about 1400°C.

Table - 3

	Thermal conductivity Btu/ft^2-hr-$^\circ$F/in.	Sp.ht. Btu/lb$^\circ$F	Bulk density lb/ft^3
High alumina brick	12	0.27	140
Fireclay brick	9	0.26	120

CHAPTER 3 : FURNACE NO.1

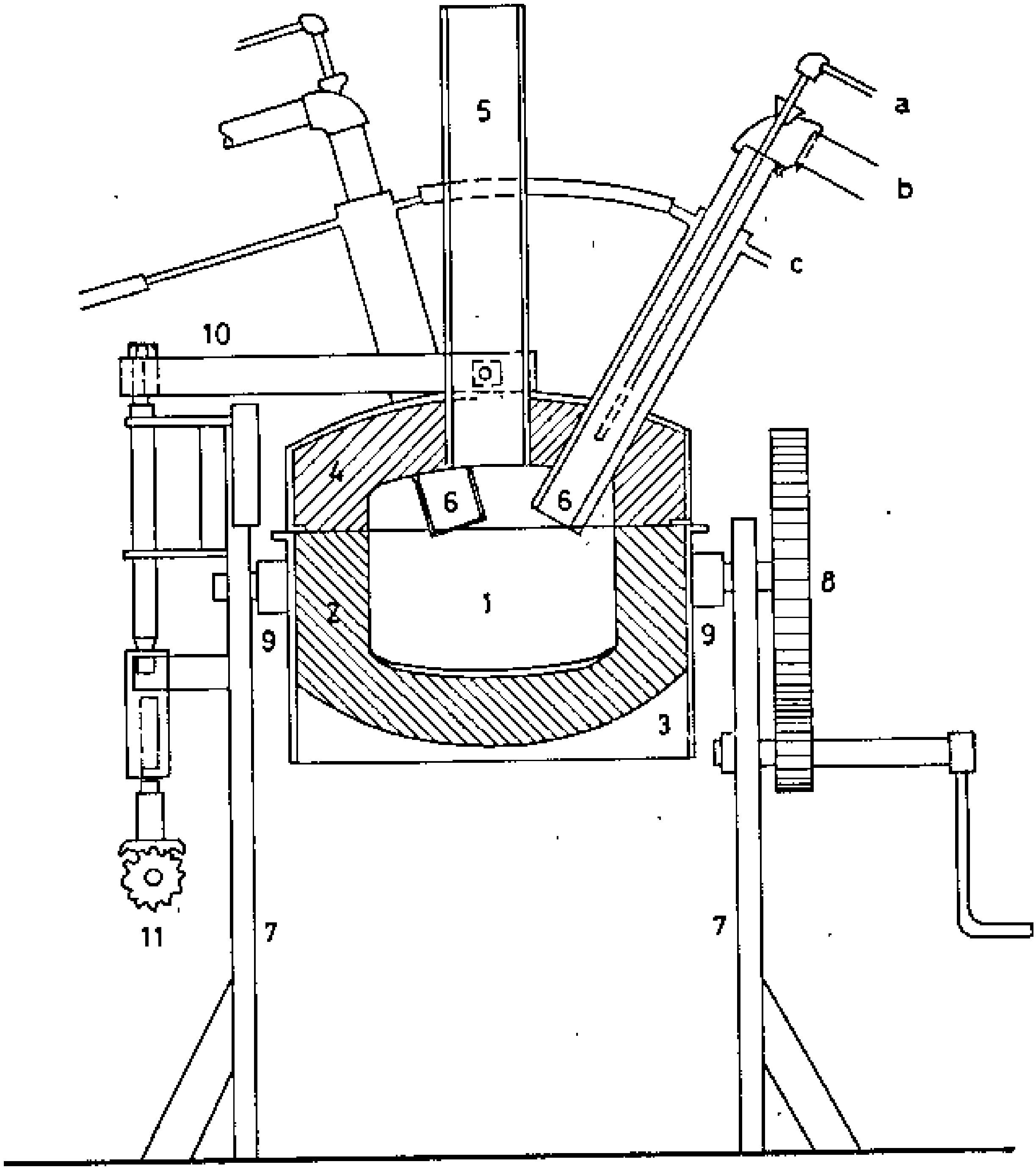
3.1 Features of construction

It has already been mentioned that the factors to be considered for the initial design of a crucible furnace are size, shape, fuel, fuel-air ratio, etc. Given a proper design of the furnace the thermal efficiency usually depends on the correct fuel air ratio, where too much fuel or too much gas are both uneconomical so far thermal energy is concerned. The optimum fuel air ratio depends also on the size and shape of the furnace.

The hearth of the furnace was initially designed to serve the purpose of crucible where natural gas was burned to melt iron for casting. The furnace body was a steel cylinder of 18 inches diameter with a height of 15 inches. The furnace wall was lined with super duty fireclay bricks 4½ inches thick. The furnace was provided with a moveable top fitted with three burners and with an exit for the products at the centre. To protect each end of the burner a cooling systen was provided as shown in Fig.7. The furnace top was built up with a mixture of grog and fire clay. The furnace body was supported on two parallel stands by means of trunions. A gear wheel was attached with a rotary handle fitted with one of the stands for tilting the furnace to withdraw the molten metal.

3.2 Experiments and results

A few experiments were carried out with pig iron/cast iron



1 Furnace body
2 Refractory lining
3 Furnace shell
4 Furnace top (movable)
5 Exhaust port
6 Burners
  (a) Gas supply
  (b) Air supply
  (c) Cooling water
7 Furnace stands
8 Tilting wheel
9 Trunions
10 Lifting arm
11 Bevel gear for lifting the furnace top.

Fig. 7 Furnace No. 1

blocks but it was never possible to obtain liquid metal even after a continuous running of 3 hours. A solid lump of semifused metal was obtained with a brittle oxidized black layer on its surface. The oxidized layer was analysed and was found to contain about 44% SiO_2. A representative micro-structure of the layer is given in Fig.8.

It was, therefore, concluded that this furnace was unable to develop sufficient temperature to melt pig/cast iron and a drastic modification in the design of the furnace was necessary.

CHAPTER 4 : THE MODIFIED FURNACE

4.1 DESIGN AND CONSTRUCTION

It was observed that the development of sufficient temperature to get cast iron in fluid condition was not possible with Furnace No.1 even by using three burners. The following major changes were, therefore, included in the modified furnace (Fig.9):

Tap hole and partial tilting arrangement

The position/alignment of the burner and the mode of combustion

The furnace top

The exhaust flue and charging

Refractory lining

The hearth

4.1.1 Tap hole and partial tilting arrangement

In Furnace No.1 there was arrangement for withdrawal of the molten metal by completely tilting the furnace while in the case of the modified furnace a tap hole was provided at the bottom (Fig.10). It is a tapered hole passing through furnace lining. Its diameter varies from 1½" at the inner end to about 1¼" at the outer end. The axis of the tap hole was at an angle of about 15° so that by partial tilt, molten metal could easily be withdrawn from the hearth of the furnace.

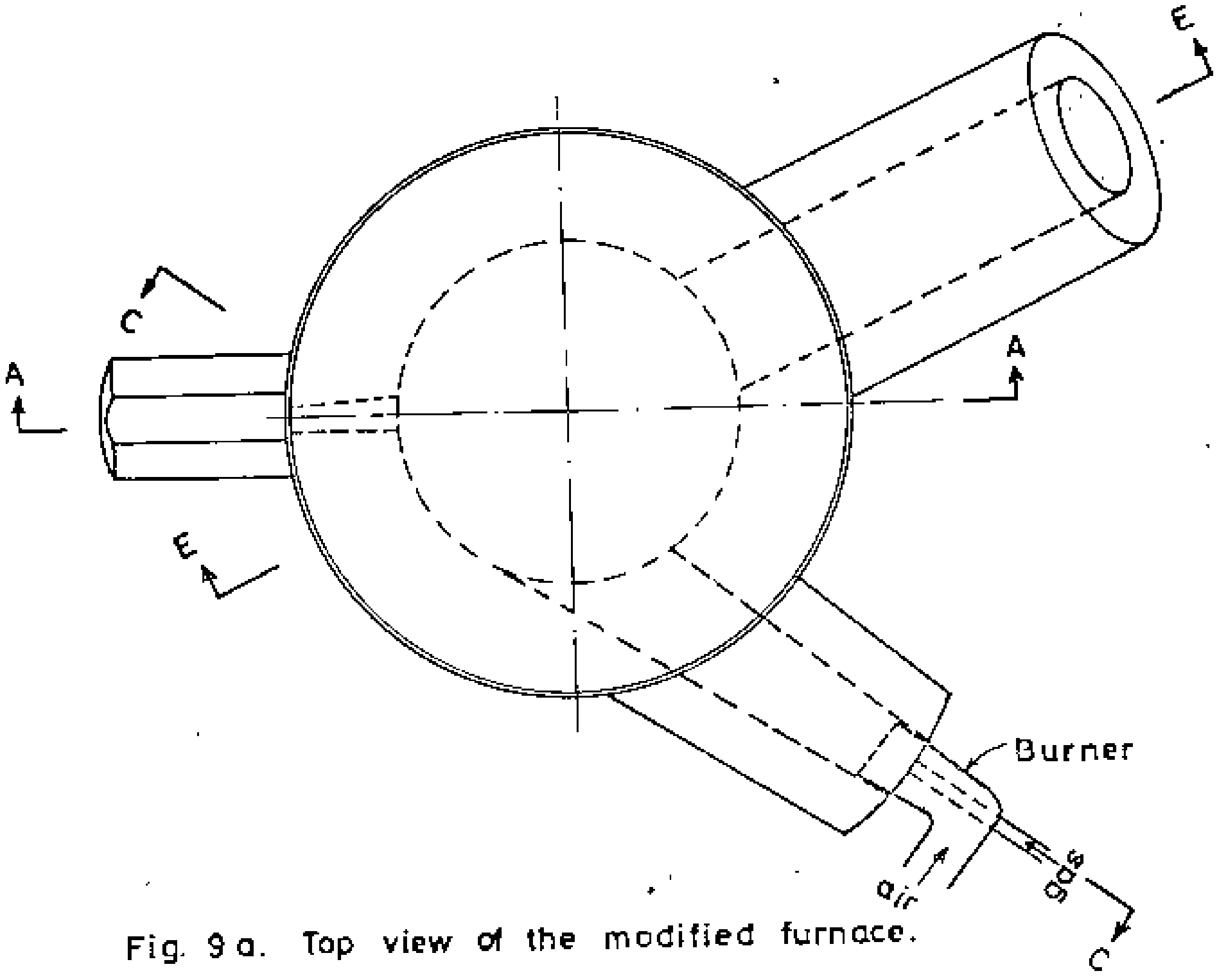


Fig. 9a. Top view of the modified furnace.

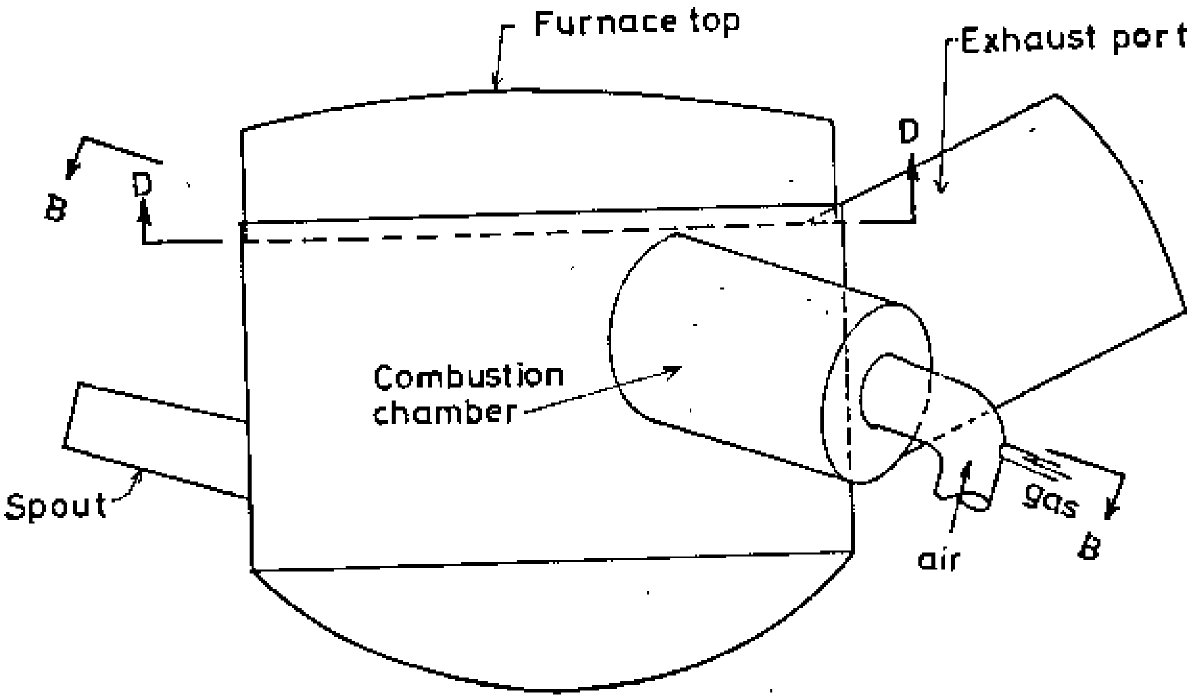


Fig. 9b. Side view of the modified furnace.

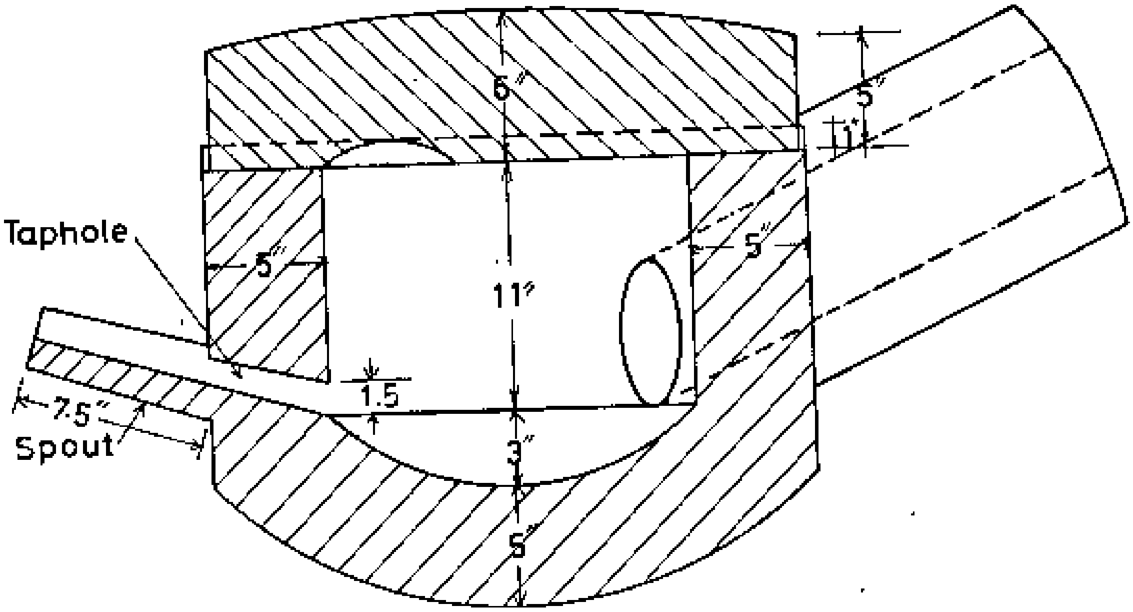


Fig. 10 Sectional view at A-A (Fig. 9a) showing the tape hole.

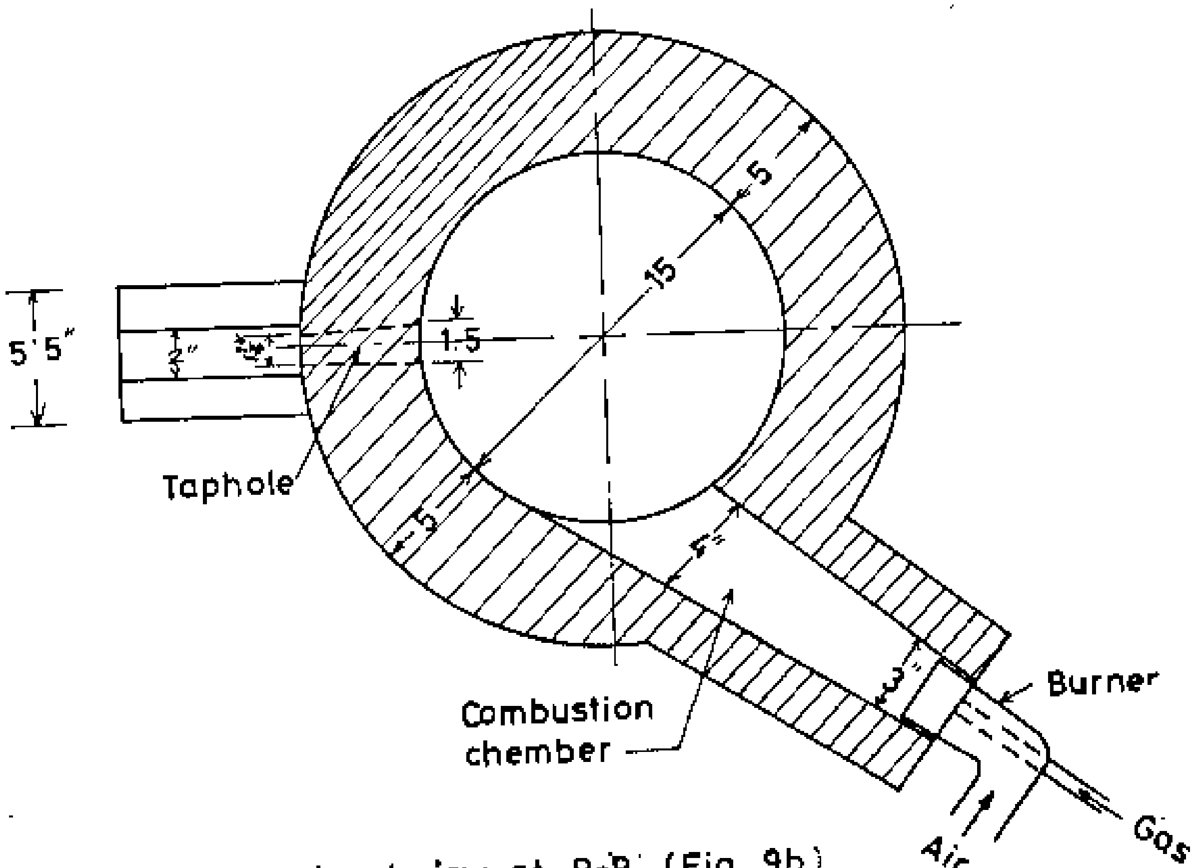


Fig. 11 Sectional view at B-B (Fig. 9b) showing the burner.

4.1.2 The position/alignment of the burner and the mode of combustion.

In the modified design a single burner (without any arrangement for water cooling whatsoever) was placed almost tangential to the furnace body (Fig.11) so that the combustion product might have a circular motion inside the furnace before it passed out through the exhaust port.

In Furnace No.1 the mixture of air and gas led inside the furnace for direct combustion just over the charge, while in the modified furnace a combustion chamber was provided before entrance to the furnace, so that the hot flue from the combustion chamber could enter the furnace after combustion. To avoid the oxidation of the charge the flue from the combustion chamber was directed upward so that before complete combustion the flue might not come into contact with the charge. The burner was also placed in such a way that the hot flue, reflecting from the top, comes first in the tap hole region (Fig.12). This was done to get maximum temperatures of the molten bath near the tap hole.

4.1.3 The furnace top

The top of the furnace is stationary in this case, the inner surface of which is slightly curved (Fig.12 & 13). The burner was directed slightly upward so that the flue strikes the inner surface of the top tangentially before making circular rotation (Fig.12). The thickness of the top lining is about 5".

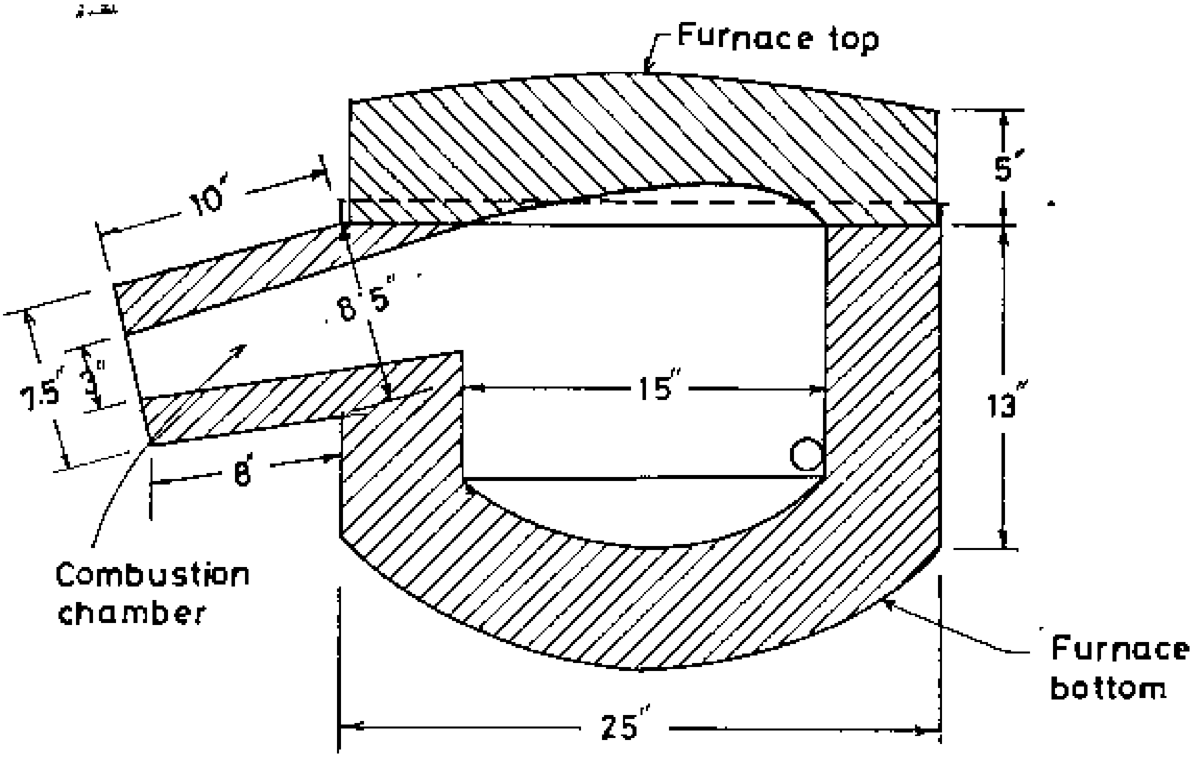


Fig. 12. Sectional view at C-C (Fig: 9a) showing the furnace top.

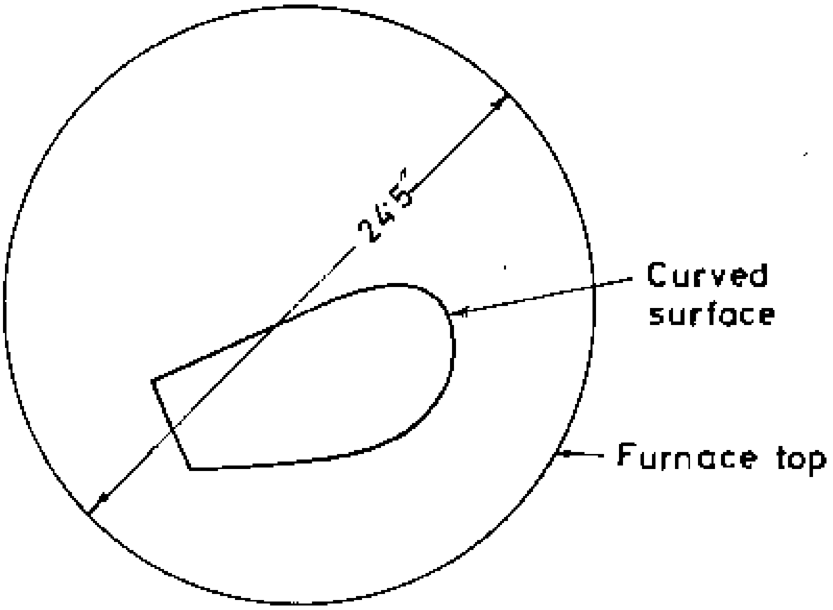


Fig. 13. Sectional view at D-D (Fig. 9b) showing the inverted view of the furnace top.

The lining was made by high alumina fire brick aggregates with high alumina fireclay cement. The lining is reinforced with mild steel rods which is welded with the outer shell of the furnace top.

4.1.4 The exhaust flue and charging

The exhaust port of this modified furnace (Fig.14) was made slightly wider than that in theformer one. It was made by mild steel sheet rigidly fitted with the furnace shell and lined with high alumina brick aggregate with high alumina fire clay cement. The raw materials or pigs to be melted are charged through this exhaust port to recover some heat from the exhaust flue. The inner diameter of the port is about 5.5", sufficient to charge the medium sized pig iron block or any other reasonable sized scrap materials.

Optical pyrometer readings indicated that the charged materials are pre-heated in the exhaust port to temperatures between 700-800°C at the external end to temperatures of 1100-1150°C at the inner end by the exhaust flue before reaching the hearth.

4.1.5 Refractory lining

The wall thickness is also an important part of furnace design. The heat loss through the wall depends on the inside and outside wall temperatures, the insulating property of the refractory brick and the thickness of the wall. The desired inside

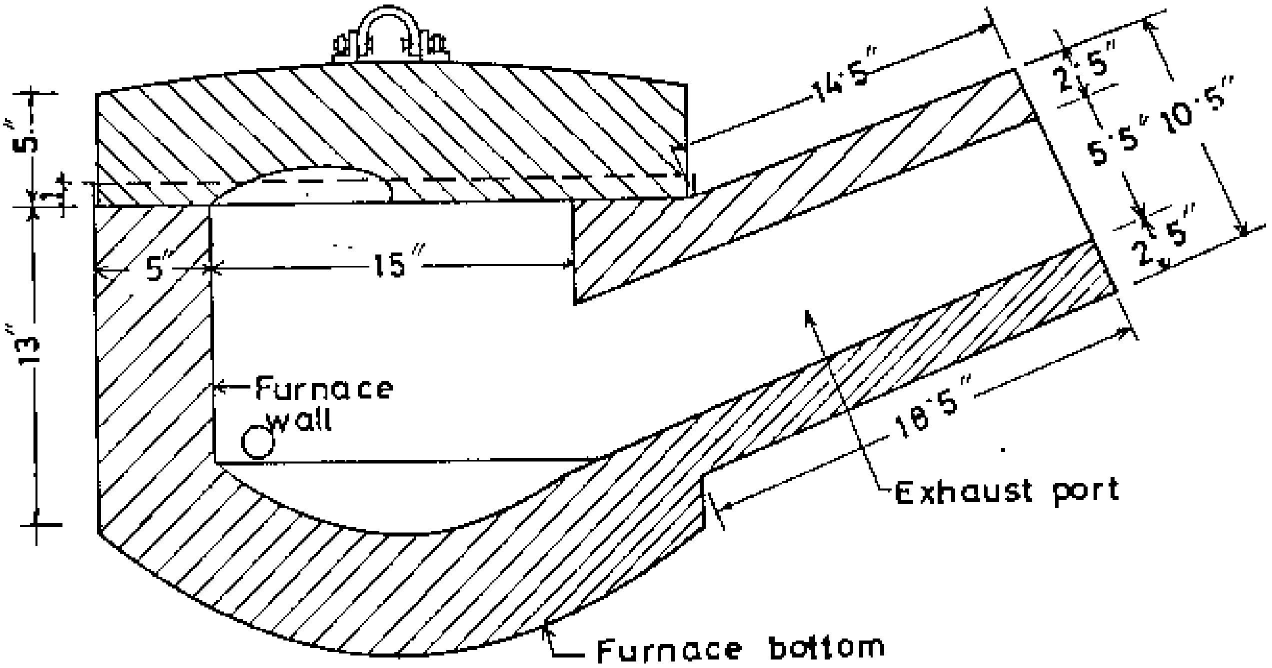


Fig. 14. Sectional view at E-E (Fig. 9a) showing the exhaust port.

temperature of the furnace is around 1400°C. Considering the above factors, the thickness of the furnade wall was chosen to be between 4½-5".

In the first furnace, super duty fireclay bricks and clay were used for the lining of the furnace. It has already been mentioned that the charge was not sufficiently fluid enough to get good castings. In the modified furnace same quality of bricks and clay were used. In the first few experiments the bricks and the lining materials were found to be vitrified and fused in some places. Readings with Pt/Pt-10%Rh thermocouple indicated a temperature of 1380°C-1410°C near the inner surface of the furnace wall on more than one occasion. It was, therefore, considered reasonable that the bricks as well as the clay be replaced by some high alumina bricks and mortar. In service, this material was found to be quite resistant to the temperature attained in the furnace.

Difficulty was experienced in the construction of the top, both in the first and the second furnaces. The top was subjected to the high heat and to the impact of hot flue and showed spalling of fused masses in both cases. Good result was found by introducing mild steel net re-inforcements and by using high alumina refractory grog and high alumina fireclay cement. It is considered that some heat-resisting material such as nichrome wire may be used to overcome this difficulty but it was not possible to use such wires in the experiments under discussion.

4.1.6 The hearth

The hearth of the second furnace was a spherical one compared to the initial furnace where the furnace hearth was more or less a flat bottomed one. Since this furnace was only an experimental one, it was designed to hold liquid metal of about 70 lbs. for each tap. Because the hot flue gases would naturally stay in the furnace hearth for a short time and would pass out through the exhaust port carrying sufficient sensible heat, heat storage was likely to be poor. This would obviously mean that hearth having a large surface area exposed to the hot gases, with a relatively shallow depth would favour a rapid transfer and efficient storage of heat in the molten charge. The surface area of the hearth was, therefore, made large compared to its average depth, because a larger surface area would receive more heat by contact with the flue gases and by radiation from the roof as well as from the wall of the furnace. The maximum depth (h) of the hearth was 3" inches (Fig.15).

Density of cast iron = 442 lbs/cft.

Volume of molten pig iron per tap = $\frac{70}{442}$ cft.

= $\frac{70}{442}$ X 12X12X12 cubic inches

= 274 cubic inches.

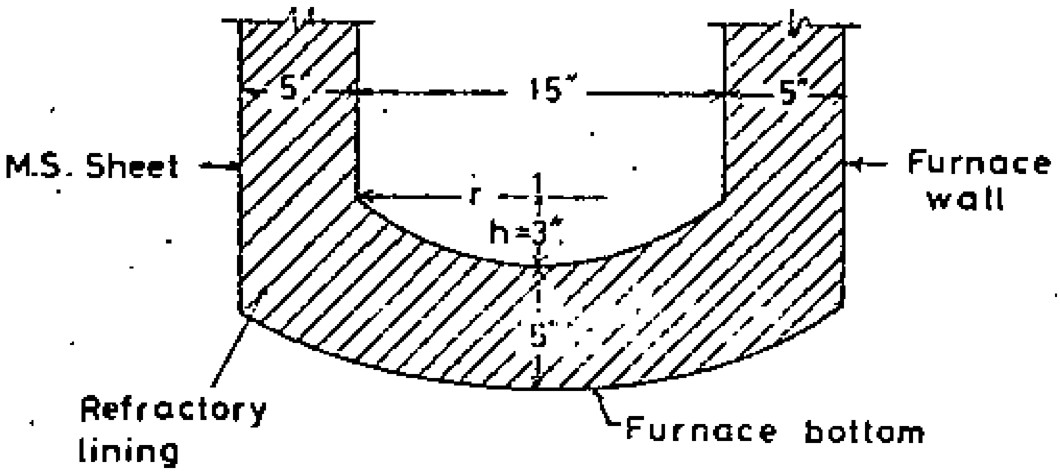


Fig. 15. Sectional view of the hearth

Now, if R be the radius of curvature of the spherical hearth, volume of the hearth would be

$$V = \frac{\pi}{3}h^2(3R-h)$$

From Fig.15,

$$R^2 = r^2+(R-h)^2$$

$$\text{or, } 2Rh = r^2+h^2$$

$$\text{or, } R = \frac{r^2+h^2}{2h}$$

$$\therefore V = \frac{\pi}{3}h^2\left(\frac{3r^2+3h^2}{2h} - h\right)$$

$$= \frac{\pi}{6}h(3r^2+h^2)$$

$$\text{or, } 274 = \frac{\pi}{6}\times 3(3r^2+3^2)$$

$$= \frac{\pi}{2}(3r^2+9)$$

$$= \frac{3\pi}{2}r^2 + \frac{9\pi}{2}$$

or, $r = 7.43''$

or, Diameter $d = 2r = 14.86''$

$\therefore$ Diameter of the hearth was taken to be 15 inches. This diameter was same as the diameter of the stack.

4.1.7 Overall furnace dimension :

The over-all furnace dimensions may be summerised as follows:

The furnace basically consists of a 'movable top', a body and a hearth with a spherical bottom. It has already been mentioned that stratification may occur in deep section of the furnace. To avoid the stratification of hot and cold gas the stack height is kept small. This was chosen to be about 11".

The internal diameter of the furnace, d = 15"

Thickness of wall, T = 5"

∴ The external diameter of the furnace body

= d + 2T

= 15" + 2 X 5"

= 25 inches.

Maximum thickness of the furnace top was taken about 6".

The total heighet of the furnace

= stack height + thickness of top + height of hearth + thickness of borrom = 11" + 6" + 3" + 5"

= 25 inches.

4.2 EXPERIMENTS AND RESULTS

After the construction of the furnace few days were allowed for curing the lining. The burner was connected with the blower and the gas line. The furnace top was placed in position. The furnace was then fired at low temperatures(i.e.about 250°C), and held for 2-3 hours for the removal of moisture in the lining. A few crecks were observed here & there in the lining and they were patched with high alumina clay. It was then fired at elevated temperature. A Pt/Pt-10%Rh thermocouple was placed through a hole in the wall to measure the inside temperature of the furnace.

The furnace was fired and two pieces of solid pig were placed in the exhaust port. This was done to utilize the sensible heat of the flue gases. Within a very short period the furnace interior became white hot and the first one of the pig iron was melted and stored in the hearth. The other piece of pig iron which was preheated by the flue gas was pushed toward the hearth and another piece of pig iron was placed in that position. When the former one was melted and accumulated in the hearth the latter one was pushed. Within a very short period it was also melted and accumulated in the hearth. A few minutes were allowed so that the molten metal became super heated (about a temperature of 1350°C) and then tapped in a previously heated ladle for casting. It was found that the molten metal was sufficiently fluid for sound casting. The operation was repeated twice and a similar result was obtained within a shorter time.

Two other similar experimental runs were conducted placing an orifice meter in the air line. Gas line was already provided with a meter. The initial and final readings of gas meter were noted and the gas flow per minute was found out. This reading was at 8 psig. So it was converted to normal atmospheric pressure (14.7 psia). Manometer reading of the orifice meter was also noted and from the difference of height of water, air flow was calculated.

Table-4.

Run Nos.	Date of Expt.	Wt. of metal charged (lb.)	Flow of gas/min (cft)	Flow of air/min (cft)	Inside temp. of furnace (°C)	Flue gas temp. (°C)	Time in mins.	Remarks
1.	14.11.79	70	▲	*	1380	-	30	Fluid metal obtained for sound casting
2.	"	70	▲	*	1410	-	25	"
3.	"	70	▲	*	1410	-	25	"
4.	22.5.81	70	4.73	84.89	1350	935	35	"
5.	"	70	"	"	1350	935	30	"

▲ Gas readings were not possible for unavoidable reasons.

* Without orifice meter in the air line.

It is apparent from the above data that with the introduction of the orifice meter in the air line, the maximum temperature attainable in the furnace was considerably less than that obtained without the orifice meter in the line. Therefore, it seems possible to obtain higher temperatures by increasing the supply of air for combustion in the modified furnace.

CHAPTER 5 : DISCUSSION

Investigations were conducted with Furnace No.1 where heating was done by three burners in the furnace top. The charge was kept on the hearth of the furnace. The top with the exhaust was a movable part and the charging was done by moving the top aside. The semifused mass left at the end of the heat could only be taken out of the furnace with much difficulty. Subsequent observations showed that the surface of the material was heavily oxidized and was very much porous. It was observed that the refractory lining at and around the base of the exhaust port as well as the inner surface of refractory lining of the furnace top were more or less vitrified whereas the rest of the refractory lining comprising the furnace wall was not so much affected. It was, therefore, concluded that the combustion largely took place beneath the furnace top releasing the maximum amount of heat in this region instead of the furnace hearth. As a result, temperature in the furnace hearth was not sufficient to melt the charge. The following modifications in the design of the furnace were, therefore, considered to be essential:

1. Since combustion was taking place inside the furnace and there was no separate combustion chamber for the gases prior to the entrance in the furnace, the first necessary modification was, therefore, considered to be the addition of a separate combustion chamber for this purpose.

2. A further essential modification was introduced in the alignment/direction of the burner. It was observed that even with the provision of the combustion chamber in an intermediate modification of the furnace, but with the burner directed towards the bottom, sufficient temperature could not be developed to melt the charge. It was considered that the length of flame-travel within the furnace was still insufficient and the combustion was not probably complete. Therefore, it was finally decided to further increase the length of flame-travel by directing the flame towards the top where from the hot gases could be made to impinge upon the charge after reverberation. This arrangement proved to be effective to develop the required temperature.

3. The exhaust in Furnace No.1 was situated at the centre of the furnace top and the withdrawal of flue gases was quick resulting in large loss of heat. In the final modification, the exhaust was placed at as much a low level in the furnace body as possible, to increase the period of stay of the flue gases in the furnace, thereby minimizing the loss of heat.

4. In the initial arrangement the furnace top was to be moved aside and the furnace body was to be tilted through an angele of more than 90° for the complete removal of the molten metal. This operation would require sufficient time with a large loss of heat. Furthermore, lifting of the heavy top and pushing it aside along with the burners and the cooling water pipes were rather laborious and inconvenient. In the final modified furnace,

the removal of the top during tapping of the molten metal was eliminated by providing a tap hole at the base of the hearth. Additionally, this arrangement also made it possible to tap the molten metal by slight tilting (about 20-30^{0}).

A modified furnace was accordingly built incorporating the above features, which proved to be successful to develop necessary temperature for melting the charge.

APPENDIX - A

ESTIMATION OF FURNACE MATERIALS

The major materials used for the construction of the furnace are refractory bricks, refractory clay and m.s.sheet. The approximate amounts of these materials required are estimated as follows:

1. Refractory bricks

Two types of high alumina bricks were used for the construction of the furnace - (a) taper bricks of size 9"X4½"X (3" to 2½") for the furnace wall and (b) standard bricks of size 9"X4½"X 3" to produce aggregate for furnace top, bottom, exhaust and combustion chamber.

If d and D be the inner and outer diameters of the furnace respectively and H be the height of the wall,
Approximate volume of the furnace wall (Fig.10 and 11)

$$= \frac{\pi}{4}(D^2-d^2) \times H$$

$$= \frac{\pi}{4}(25^2 - 15^2) \times 11$$

$$\approx 3456 \text{ cubic inches.}$$

Approximate volume of the furnace top (Fig.12 and 13)

$$= \frac{\pi}{4} \times (\text{diameter})^2 \times \text{thickness}$$

$$= \frac{\pi}{4} \times (24.5)^2 \times 5$$

$$\approx 2358 \text{ cubic inches.}$$

Approximate volume of furnace bottom (Fig.12)and 15)

$$= \frac{\pi}{4} X (\text{diameter})^2 X \text{ thickness}$$

$$= \frac{\pi}{4} X\ 25^2\ X\ 5$$

$$\approx 2455 \text{ cubic inches.}$$

Approximate volume of the lining of the exhaust port (Fig.14)

$$= \frac{\pi}{4}(10.5^2 - 5.5^2)\ X\ \frac{18.5 + 14.5}{2}$$

$$\approx 1037 \text{ cubic inches.}$$

Approximate volume of the lining of combustion chamber(Fig.12)

$$= \frac{\pi}{4}\left[\left(\frac{8.5 + 7.5}{2}\right)^2 - \left(\frac{4+3}{2}\right)^2\right] X\ \frac{10 + 8}{2}$$

$$\approx 366 \text{ cubic inches}$$

$$\text{Volume of 1 taper brick} = 9X4.5\ X\ \frac{3 + 2.5}{2}$$

$$= 111.38 \text{ in}^3.$$

∴No. of taper bricks required

$$= \frac{\text{volume of furnace wall}}{\text{volume of 1 taper brick}}$$

$$= \frac{3456}{111.38}$$

$$\approx 32 \text{ bricks.}$$

Total volume of aggregate required = volume of top + volume of bottom + volume of the lining of exhaust + volume of the lining of combustion chamber.

$$= 2358 + 2455 + 1037 + 366$$

$$= 6216 \text{ cubic inches}$$

Volume of 1 standard brick = $9 \times 4\frac{1}{2} \times 3 = 121.5\ \text{in}^3$

No. of standard bricks required

$$= \frac{\text{Volume of aggregate}}{\text{volume of 1 standard brick}}$$

$$= \frac{6216}{121.5}$$

$$\approx 52 \text{ bricks}$$

2. Refractory clay

The ratio of aggregate to clay was 3:1

$$\text{clay used} = \frac{6216}{3} = 2072\ \text{in}^3$$

$$= 1.2\ \text{ft}^3$$

3. The furnace shell

0.125" thick m.s. sheets were used for the construction of the external shell of the furnace. Approximate calculation of the area of sheet needed is given below :

For top(Fig.12) $25'' \times 25'' + \pi \times 25'' \times 5'' = 1017.7\ \text{in}^2 \approx 8\ \text{ft}^2$

For vertical shell(Fig.10&12) $\pi \times 25 \times 14 = 1099.56$ " ≈ 8 "

For bottom (Fig.12) $25 \times 25 = 625.00$ " ≈ 5 "

For exhaust(Fig.14) $\pi \times 10.5 \times 18.5 = 610.25$ " ≈ 5 "

For burner (Fig.12) $\pi \times 8.5 \times 10 = 267.04$ " ≈ 2 "

For spout (Fig.10&11) $\frac{\pi \times 5.5}{2} \times 7.5 = 64.80$ " ≈ 1 "

29 "

Total amount of m.s.sheet required = 29 ft^2.

APPENDIX - B

MEASUREMENT OF GAS AND AIR FLOW

(a) Measurement of gas flow

Final meter reading = 4010

Initial meter reading = 3811

Total flow of gas during 65 minutes = 199 cft at 8 psig

(Meter shows the flow of gas at 8 psig)

$\therefore$ Total flow of gas at atmospheric pressure (14.7 psia) during 65 minutes heating will be

$$\frac{199 \times (14.7 + 8)}{14.7}$$

$$= 307.3 \text{ Cft.}$$

$\therefore$ Flow of gas per minute

$$= \frac{307.3}{65}$$

$= 4.73$ cft/min. at atmospheric pressure & temp.

(b) Measurement of air flow

Diameter of air pipe = $2\frac{3}{16}$"

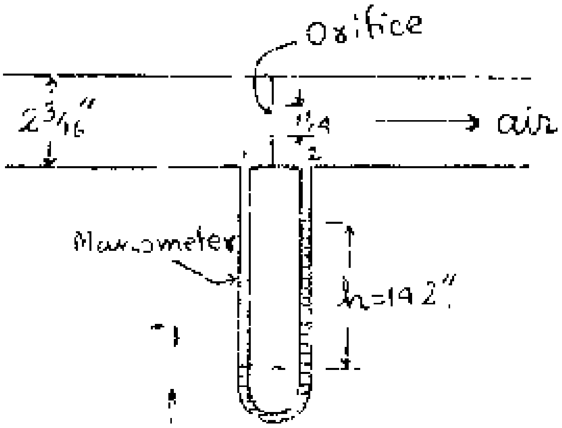
Orifice diameter = $1\frac{1}{4}$"

$C_D = 0.63$

Difference of height of water level in manometer, h = 14.2"

Specific gravity of air,

$\gamma_{air} = 0.07657 \text{ lb/ft}^3$ at 60°F and 30 in Hg.



If P_1 and P_2 be the static pressures at section 1 and 2 respectively, then $P_1-P_2 = \gamma_{water} \times$ difference of water level, ft.

$$= \gamma_{water} \times \frac{h}{12}$$

$$= 62.4 \times \frac{14.2}{12} \qquad (\gamma_{water} = 62.4 \text{ lb/ft}^3)$$

$$= 73.84 \text{ lb/ft}^2$$

Now, flow of air through section 1 and 2 are same.

Flow or air through section 1

= area of section 1 X velocity at 1.

$= \frac{\pi}{4}(2\tfrac{3}{16})^2 \times V_1$, where V_1 is the velocity at 1.

Flow of air through section 2

$= \frac{\pi}{4}(1\tfrac{1}{4})^2 \times V_2$, where V_2 is the velocity at 2.

$$\therefore \frac{\pi}{4}(2\tfrac{3}{16})^2 V_1 = \frac{\pi}{4}(1\tfrac{1}{4})^2 V_2$$

or, $V_1 = 0.32654 V_2$

Now, $\frac{P_1 - P_2}{\gamma_{air}} = \frac{V_2^2 - V_1^2}{2g}$

$$= \frac{V_2^2 - (0.32654)^2 V_2^2}{2 \times 32.2}$$

$$= \frac{0.89337V_2^{\,2}}{64.4}$$

$$\therefore V_2^{\,2} = \frac{P_1 - P_2}{\gamma_{air}} \times \frac{64.4}{0.89337}$$

$$= \frac{73.84}{0.07657} \times \frac{64.4}{0.89337}$$

$$= 69516.443$$

$$\therefore V_2 = 263.6597 \text{ ft/sec.}$$

Theoretical flow, $Q_t = A_2V_2$

Actual flow $Q = A_2V_2 \times C_D$

$$= \frac{\pi}{4}\,\frac{(1\tfrac{1}{4})^2}{144} \times 263.6597 \times 0.63 \times 60$$

$$= 84.89 \text{ cft/min.}$$

(specific gravity of air increases with the pressure and decreses with the rise of temp.

During operation static pressure inside the pipe was slightly above atmospheric and the temperature was also slightly above 60°F. Therefore in calculation the value of γ_{air} was taken at 60°F and 30 in Hg.

APPENDIX - C

HEAT BALANCE IN STEADY STATE CONDITION

Heat balance for the steady state operation of the furnace is discussed below.

The major items of heat input are :

a) Chemical energy of the fuel which is equal to the product of flow rate of fuel and its calorific value. If the gross calorific value is used then unless the latent heat of condensation of steam can be utilized the efficiency of the process will workout to be lower than if the net value is used.

b) The sensible heat of the fuel and the air at their respective temperatures.

c) Heat contained in cold pig iron during charging.

The items of heat distribution can be divided into the following major heads :

d) Heat content of liquid pig iron.

e) The sensible heat of the products of combustion.

f) Radiation through the openings (tap hole and exhaust port).

g) Heat loss from the surface of the furnace by radiation and convection.

(a) Chemical energy of fuel
Composition of Tital gas (5)

CH_4 = 96.9%

C_2H_6 = 1.8%

C_3H_8 = 0.5%

C_4H_{10} = 0.2%

N_2 = 0.3%

CO_2 = 0.3%

Calorific value (13) of :

CH_4 = 962 Btu/ft^3(at N.T.P)

C_2H_6 = 1698 "

C_3H_8 = 2433 "

C_4H_{10} = 3171 "

∴ Calorific value of Titas gas is

0.969 X 962 + 0.018 X 1698 + 0.005 X 2433 + 0.002 X 3171

= 981.25 Btu/ft^3

Flow rate of gas = 4.73 cft/min at 14.7 psia and 21 °C

$$= \frac{4.73 \times 273}{273 + 21}$$

= 4.39 cft/min at N.T.P.

= 263.4 cft/hr.

Chemical energy of fuel

= 263.4 X 981.25

= 2,58,461.25 Btu per hr.

b) <u>Sensible heat in fuel</u>

Flow rate of fuel = 263.4 cft per hr.

= 7.455 cum/hr.

CH_4 in fuel = 263.4 X 0.969 = 255.23 cft = 7.224 cum

C_2H_6 " = 263.4 X 0.018 = 4.74 " = 0.134 "

C_3H_8 " = 263.4 X 0.005 = 1.32 " = 0.037 "

C_4H_{10} " = 263.4 X 0.002 = 0.53 " = 0.015 "

N_2 " = 263.4 X 0.003 = 0.79 " = 0.022 "

CO_2 " = 263.4 X 0.003 = 0.79 " = 0.022 "

The specific heats (13) of the constituent gas are :

CH_4 : (0.38 + 0.00021 t) K-cal/cum between 0 and t°C.

C_2H_6 : 0.6 + 0.00054 t "

C_3H_8 : (0.8 + 0.000675t) "

C_4H_{10} : 1.0 + 0.00081t "

N_2 : 0.302+0.0.00022t "

CO_2 : 0.406 + 0.00009t "

∴ Sensible heat-content of the fuel at room temperature, 70°F(21.11°C):

For CH_4 : 7.224(0.38 + 0.00021t)t = 58.63 K-cal.

C_2H_6 : 0.134(0.6 + 0.00054t)t = 1.73 "

C_3H_8 : 0.037(0.8 + 0.000675t)t = 0.64 "

C_4H_{10} : 0.015(1.0 + 0.00081t)t = 0.32 "

N_2 : 0.022(0.302 + 0.000022t)t 0.14 ".

CO_2 : 0.022(0.406 + 0.00009t)t= 0.19 "

Total = 61.65 K-cal.

= 244.64 Btu.

Sensible heat in air

Flow rate of air = 84.89 cft/min at room temperature(70°F)

∴ Flow rate of air at N.T.P. will be

$$84.89 \times \frac{32 + 460}{70 + 460} = 78.8 \text{ cft/min.}$$

= 4728 cft/hr.

= 133.81 cum/hr.

∴ Sensible heat

= 133.81(0.302 + 0.000022t)t, (13), room temp. = 70°F=21.11°C

= 854.38 K-cal per hr.

= 3390.4 Btu per hr.

c) Heat content of cold pig iron

Melting rate of pig iron = 70X2 = 140 lbs. per hr.

Mean specific heat of pig iron from 0-21°C can be taken as 0.135 lb-cal/lb (13)

Heat content in cold pig iron at room temperature

= 140 X 0.135 X 21

= 396.9 lb-cal

= 714.42 Btu.

d) Heat content of liquid pig iron at 1300°C.

Melting point of pig iron is assumed to be 1150°C (13)

Heat content of liquid pig iron at the melting point

= 230 lb-cal/lb (13)

Specific heat of liquid pig iron = 0.15 lb-cal/lb (13)

Heat content of liquid pig iron

= 140 X 230 + 140 X 0.15 (1300 - 1150)

= 35,350 lb-cal

= 63,630 Btu.

e) Sensible heat in the products of combustion

The combustion reactions are :

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

$$C_2H_6 + 3.5O_2 = 2CO_2 + 3H_2O$$

$$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$$

$$C_4H_{10} + 6.5O_2 = 4CO_2 + 5H_2O$$

For 1 cum. gas

$CO_2 = 0.969 + 0.018 \times 2 + 0.005 \times 3 + 0.002 \times 4$

$+ 0.003$(in gas) $= 1.031$ cum.

$H_2O = 0.969 \times 2 + 0.018 \times 3 + 0.005 \times 4 + 0.002 \times 5$

$= 2.022$ cum.

Theoretical O_2 reqd.

$= 0.969 \times 2 + 0.018 \times 3.5 + 0.005 \times 5 + 0.002 \times 6.5$

$= 2.039$ cum.

Theoretical air requd. $= \frac{2039}{0.21} = 9.71$ cum.

Total volume of CO_2 in flue gas

$= 1.031 \times 7.455 = 7.69$ cum/hr.

Total volume of H_2O in flue gas

$= 2.022 \times 7.455 = 15.07$ cum/hr.

Theoretical air reqd. $= 9.71 \times 7.455 = 72.39$ cum/hr.

Vol. of excess air $= 133.81 - 72.39 = 61.42$ cum/hr.

N_2 in theoretical air $= 72.39 \times 0.79 = 57.19$ cum.

N_2 in gas $= 7.455 \times 0.003 = 0.022$ cum.

Total vol. of O_2 and N_2 = vol. of N_2 in theoretical air+vol. of

N_2 in gas + vol. of excess air = 57.19 + 0.02 + 61.42 = 118.63 cum.

Now, sensible heat loss in flue gases

For CO_2 : 7.69(0.406 + 0.00009t)t (t = 935°C)

= 3,524.25 K-cal

For H_2O : 15.07(0.373 + 0.00005t)t

= 5,914.47 K-cal

For O_2 & N_2 : 118.63(0.302 + 0.000022t)t

= 35,779.15 K-cal

∴ Total heat loss in flue gases

= 3,524.25 + 5,914.47 + 35,779.15

= 45,217.87 K-cal/hr. = 1,79,435.99 Btu/hr.

Alternatively,

Total volume of flue gases

= vol. of CO_2 + vol. of H_2O + vol. of O_2 & N_2

= 7.69 + 15.07 + 118.63

= 141.39 cum.

= 4995.65 cft.

Volume of excess air = 61.42 cum = 2170.12 cft.

∴ Percentage of air in the mixture of combustion gas and air

$$= \frac{2170.12}{4995.65} \times 100$$

= 43.44%

Now, from Fig.5 heat content of combustion gases at 935°C

= 20.5 CHU/cu.ft(N.T.P).

∴ Total heat content in flue gases = 20.5X4995.65 = 102410.82 CHU

= 184339.47 Btu.

f) Heat loss through the tap hole and the exhaust port by radiation :

Through tap hole :

Diameter of the hole = 1.5"

Thickness of wall = 5.0"

Furnace temperature = 1350°C(2462°F)

Now, area of equivalent diaphragm $= \frac{\pi}{4}(1.5)^2$

= 1.77 sq. in.

∴ From Fig.3, black body radiation from 1 sq in. of surface at 2462°F = 855 Btu /hr.in^2

∴ Heat loss from freely exposed diaphragm

= 855 X 1.77 = 1513.35 Btu. / hr.

The ratio, $\frac{\text{Diameter of the hole}}{\text{Thickness of wall}} = \frac{1.5}{5} = 0.3$

From Fig. 4, total radiation factor for round opening is found to be 0.25. The actual radiation through opening then is 1513.35X0.25 = 378.34 Btu per hr.

Through exhaust port

Diameter of the exhaust port = 5.5"

Thickness of the wall = 22"

Area of equivalent diaphragm = $\frac{\pi}{4}(5.5)^2$ = 23.76 sq.in.

∴ Heat loss from freely exposed

diaphragm = 855 X 23.76 = 20314.8 Btu/hr.

The ratio, $\frac{\text{Diameter of the port}}{\text{Thickness of wall}} = \frac{5.5}{22} = 0.25$

From Fig. 4, total radiation factor is found to be 0.217

∴ The actual radiation through the opening then is

20314.8 X 0.217 = 4408.31 Btu per hr.

∴ Total heat loss through openings :

= 378.34 + 4408.31 = 4786.65 Btu per hr.

g) Heat loss from the surface of the furnace

a) By radiation

Approximate surface area of

top = $\frac{\pi}{4}(25)^2$ = 491 sq. in = 3.41 sq.ft.

Area of vertical surface = π X25X(13+5)

= 1413.72 sq. in = 9.82 sq. ft.

Approximate surface area of furnace

botton = $\frac{\pi}{4}(25)^2$ = 491 in^2 = 3.41 ft^2

Surface area of exhaust = π X10.5 X $\frac{18.5 + 14.5}{2}$ = 544.28 in^2

= 3.78 sq.ft.

Total area of the furnace top, bottom and vertical surface

$= 3.41 + 3.41 + 9.82 = 16.64$ sq. ft.

Surface temperature of the furnace = 150°C (302°F)

Temperature of the surface of exhaust port = 200°C (392°F)

Ambient air temperature = 100°F

Emissivity of steel may be taken as 0.82 (8)

∴ Heat loss by radiation from top, bottom and side walls

$$= 0.173 \times 16.64 \times 0.82 \left(\frac{302+460}{100}\right)^4 - \left(\frac{100+460}{100}\right)^4$$

= 5637.07 Btu per hr.

Heat loss by radiation from the surface of the exhaust port

$$= 0.173 \times 3.78 \times 0.82 \left(\frac{392+460}{100}\right)^4 - \left(\frac{100+460}{100}\right)^4$$

= 2298.24 Btu/hr.

∴ Total heat loss from the surfaces by radiation,

Hr = 5637.07 + 2298.24 = 7935.31 Btu/hr.

b) <u>By convection</u>

Heat loss from the top (C=0.39)

$$= 0.39 \times 3.41(302-100)^{1.25}$$

= 1012.76 Btu/hr.

Heat loss from the bottom (C = 0.2)

$$= 0.2 \times 3.41 \times (302-100)^{1.25}$$

= 519.37 Btu/hr.

Heat loss from vertical surface (C = 0.3)

$$= 0.3 \times 9.82 \,(302 - 100)^{1.25}$$

= 2243.48 Btu/hr.

Heat loss from the surface ofthe exhaust (C = 0.35)

$$= 0.35 \times 3.78(392-100)^{1.25}$$

$$= 1596.94 \text{ Btu per hr.}$$

Total heat loss from the surfaces by convection,

$$Hc = 1012.76 + 519.37 + 2243.48 + 1596.94$$

$$= 5372.55 \text{ Btu per hr.}$$

∴ Total heat loss from the surfaces by radiation and convection,

$$Hr + Hc = 7935.31 + 5372.55$$

$$= 13{,}307.86 \text{ Btu per hr.}$$

Now, the heat balance in the steady state condition is given in Table below :

Table 5 : Summary of Heat Balance in steady state condition

Heat input (Btu)/hr.		Heat output (Btu)/hr.	
Chemical energy of gas=	2,58,461	Heat in liquid pig =	63,630
Sensible heat in gas =	245	Sensible heat in flue gases =	1,79,436
Sensible heat in air =	3,390	Heat loss through openings =	4,787
Heat content of cold pig iron =	714	Heat loss from the surface =	13,308
Total =	2,62,810	Total =	2,61,161

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