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RESEARCH ARTICLE

Hydrocarbon fuels, combustion characteristics & insulating refractories in industrial furnace

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Abstract: Liquid fuels like Furnace Oil, Light distillate oil, Diesel & gaseous fuels like PNG (Piped Natural Gas), LPG (Liquefied Petroleum Gas) are predominantly used at present in industrial applications. Single fuel, Dual fuel & Multi-fuel options are available in the market. All these fuels are called hydrocarbon fuel. A loss of drop of oil in every second can waste about 4000 liters in a year. Selection of right type of fuel depends on various factors like availability, storage, handling, Pollution & landed cost of the fuel. These different fuels used for combustion in industrial furnace are discussed herewith. Complete combustion in industrial furnace enhances efficiency, control pollution as well as global warming. Efficient use of fuel leads to complete combustion. This paper deliberates about combustion of fuel and how complete combustion is to be achieved in industrial furnace. Stoichiometric ratio ensures complete combustion. Industrial furnace uses refractories to form a combustion chamber with proper insulation to ensure temperature within the combustion chamber is as per requirement of the job. The outside skin temperature of industrial furnace is about 35ºC to 45ºC from safety point of view. To maintain this temperature difference with minimum wall thickness needs proper refractory selection which must withstand high temperature. The main objective of this research paper is to propose strategies to select the right fuel, proper insulating material to achieve complete combustion & minimum heat losses through the walls of combustion chamber. This will help in making an efficient design and optimize combustion controls to keep heat losses at minimum level.

Keywords: hydrocarbon, combustion chamber, multi-fuel, stoichiometric ratio

1 Introduction

North American definition of furnace is: An appliance fired by gas or oil in which air or water is heated to be circulated throughout a building in a heating system. Combustion took place in the furnace which is a chemical reaction of carbon from hydrocarbon fuel and oxygen from air in presence of ignition only [1]. The design is changing with invent of new technology, computer integration with machinery & software development. It has been found that there is need for efficient fuel combustion, minimum heat loss to save energy and cost. Today many fuel, combustion equipment & refractory material options are available in the market. Choosing the correct one is a key to successes. Hence detailed study of fuel, combustion & refractory material is very important & discussed in this paper. Hydrocarbon is a compound of hydrogen & carbon. These are chief components of petroleum & natural gas. Fuels are divided into three categories viz. solid (example: Coal, Wood, Husk Bagasse, Briquettes, $\cdots$), Liquid (Furnace Oil, LDO-Light Distillate Oil, Petrol, Diesel, Kerosene, tar, $\cdots$), Gas (PNG, LPG, Producer Gas, Coke Oven gas, Blast Furnace Gas, coal gas, $\cdots$).

All these fuels contain carbon as a main constituent required for combustion. When hydrocarbon reacts with the oxygen from air, a chemical reaction occurs & heat is released. This heat is used to raise the temperature of charge being heated. The resulting flue gases are called POC (Products of Combustion). In POC, when CO_2 is formed, it is called complete combustion which is efficient combustion whereas when CO is formed, it is called incomplete combustion. CO formation indicates, fuel is not burnt completely & wasted because of insufficient supply of oxygen. Hence more air (oxygen) is required to ensure complete combustion [2]. Hence excess air is supplied either through burner or small tube inside the combustion chamber near the burner nozzle in the combustion chamber. Thus, complete combustion is achieved. When fuel is insufficient, it is called weak mixture & more fuel supply is required. When fuel is more than required, it is called Rich mixture & fuel supply needs to be controlled. When fuel is sufficient & in exact proportion with the air, it is called stoichiometric ratio [3,4]. In all kind of combustion including combustion in the engine of 4w automotive vehicles, Stoichiometric ratio of Air/Fuel is must for enhancing efficiency as well as pollution control. Furnace wall, roof, hearth & door is to be built up with insulating material called refractory to ensure the temperature difference between the combustion chamber & skin i.e. outside temperature of the furnace. Different types of refractories viz. Refractory Brick, Insulation Brick, Ceramic Block & ceramic fibers used for insulation purpose. Proper insulation ensures minimum heat loss through the wall, door, and leakages through openings. Hence selection of correct refractory material matters [2]. Wall thickness is based on refractory material being used, their properties like density. It is desirable to maintain proper wall thickness of the furnace. Furnace skin temperature is desirable 35^oC to 45^oC to avoid human injury from & accident near the furnace. The temperature in the combustion chamber may be to the tune of greater than 1000^oC. This difference in temperature difference can be maintained by using academics formula of heat transfer for determining the exact composite wall thickness by using suitable insulating material i.e. refractory which can withstand this high temperature as well as POC. Refractories are materials which withstand high temperature & do not fuse even at a very high temperature. Examples: Fire Clay, Silica, Chromite & Magnetite. Three basic refractory materials are available viz. 1. Acidic refractory (ex. Fire clay, Silica, Quartz) 2. Basic Refractory (ex. Bauxite, Lime, Magnesite) 3. Neutral Refractory (ex. Chromite, Graphite carbon). Industrial furnaces are concerned with insulating refractories. A refractory suitable for minimizing heat losses & thus achieving heat conservation in the furnace is called insulating refractories [2]. Industrial furnaces are concerned with insulating refractories to keep minimum heat loss through the furnace wall. They have high porosity, low thermal conductivity & high thermal insulation properties. These insulating refractories are produced from asbestos, fireclay kieselguhr. At low temperature, slag wool, glass wool & vermiculite are used. At high temperature, foam ceramics, ceramic fibre & wool are used. Refractories fusion point ranges from 1520^oC (Low heat duty) to greater than 1730^oC (Super heat duty) & accordingly for different application refractories are selected. The selection of refractories for any application is made with a view to achieving the best performance of the equipment, furnace, kiln or boiler & depends on certain properties of the refractories. The choice of refractory material for a given application will be determined by the types of furnace or heating units & the prevailing conditions viz. the gaseous atmosphere, the presence of slags, the type of metal charge required. Hence temperature is not the only criterion for selection of refractories. Any furnace designer or manufacturer should have a clear idea about the service conditions which the refractory is required to face. Besides above the following points should be considered, before selecting a refractory.

(1) Area of application
(2) Working temperatures
(3) Extent of abrasion or impact
(4) Structural load of the furnace
(5) Heat transfer & fuel conservation
(6) Cost
(7) General like availability for future

Evaluation of the above conditions & assessment of the desired properties would provide guidelines for selection of proper refractory materials. The furnace manufacturer or user is also concerned with the conservation of energy. Fuel can be saved in two ways, either by insulation or faster working. Both these methods give low energy cost per ton of product. We shall discuss Fuel, combustion & refractories in detail herewith [8].

2 Hydrocarbon fuel

Definition: A substance containing mostly carbon & hydrogen which on burning with oxygen in the atmospheric air, produces a large amount of heat. The amount of heat generated is known as calorific value (CV) of the fuel. Since the principal constituents are hydrogen & carbon, the fuel is termed as Hydrocarbon fuel [5]. Few traces of sulphur are also available which are undesirable in combustion process. Hence fuel to be selected on low sulphur content for combustion in industrial furnace. Fuels are classified into solid, liquid & gaseous fuels. Each of these fuels may be further subdivided into Natural & Prepared fuels.

2.1 Solid fuels

The natural solid fuels are wood (CV- 19700 kJ/kg), peat, lignite or brown coal, bituminous coal & anthracite coal (CV - 36000 kJ/kg). The prepared solid fuels are wood charcoal, coke, briquetted coal & pulverized coal.

The wood is converted into coal when burnt in the absence of air. Coke is produced when coal is strongly heated continuously for 42 to 48 hours in the absence of air in a closed vessel. This process is known as carbonization of coal. Coke is dull black, porous & smokeless in nature. Briquetted coal is produced from finely ground coal by molding under pressure with or without binding material. Pulverized coal is a low-grade coal with high ash content, is powdered to produce pulverized coal. Pulverized coal is popular at present & many industrial furnaces are using it as a fuel because of low running cost.

2.2 Liquid fuels

Almost all fuels are derived from natural petroleum or crude oil. The natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosene, fuel oils & lubricating oils by boiling the crude oil at different temperatures & subsequent fractional distillation or by a process such as cracking. The solid products like Vaseline & paraffin wax are recovered from the residue in the still. Petrol is the lightest & most volatile fuel distilled at a temperature from 65ºC to 220ºC. Kerosene is heavier & less volatile distilled from 220ºC to 345ºC. Heavy fuel oils are distilled after petrol & kerosene at temperatures 345ºC to 470ºC. Most commonly used fuels in industrial furnaces are Heavy fuel oil called as furnace oil, LDO, Diesel. Petrol is used in IC Engines.

2.3 Gaseous fuels

The natural gas is usually found in or near the petroleum fields, under the earth surface. It essentially consists of Marsh Gas or Methane (CH_4) together with small amount of other gases such as ethane (C_2 H_5), Carbon dioxide (CO2) & Carbon Monoxide (CO). The prepared gases are a. Coal Gas obtained by carbonization of fuel. b. Producer Gas obtained by partial combustion of coal, coke & anthracite coal in a mixed air-steam blast. c. Blast furnace gas is a by-product in the production of pig iron in the blast furnace. This gas serves as a fuel in steel works, for power generation in gas engines, for steam raising in boilers & for preheating the blast furnace. It has very low heating value about 3750 kJ/m^2. d. Coke oven gas is a by-product from coke oven & obtained by carbonization of Bituminous coal & used for industrial heating & power generation. The most commonly fuels in industrial furnaces are FO, LDO, PNG, LPG, Pulverized coal. D. Renewable fuels: With the rising cost of fossil fuel, many renewable fuels like Pulverized coal, Producer gas, Coke oven gas, Landfill gas (LFG) are developed & used at present. Renewable fuels require equipment modification. LFG is created as solid waste decomposes in a landfill. This gas consists of about 50% methane, about 50% CO2 & small amount of non-methane organic compounds. Instead of allowing LFG to escape into the atmosphere, it can be captured, converted & used as energy source. It reduces odors & other hazards associated with LFG emissions. Further it helps to prevent methane from migrating into the atmosphere & contributing to local smog & global climate change. Pressurized methane can be piped underground & burned as a renewable fuel for manufacturing facilities at a lower cost than PNG [5]. (see Table 1)

Table 1 Industrial Heating-Combustion Tool Kit 2008 [4]

Fuel Gas Characteristics	LFG (%)	PNG (%)
Gross heating Value (BTU/ft.^{3})	300 - 500	950 – 1100
Specific Gravity	1.0 – 1.2	0.6 – 0.7
Methane (CH4) content	30 – 50	85 – 95
Carbon dioxide (CO2) content	50 –7 0	0 – 5

The various types of fuels like liquid, solid and gaseous fuels are available for firing in boilers, furnaces and other combustion equipments. The selection of right type of fuel depends on various factors such as availability, storage, handling, pollution and landed cost of fuel [12]. GCV is Gross Calorific value in below table.

The knowledge of the fuel properties helps in selecting the right fuel for the right purpose and efficient use of the fuel. The following characteristics, determined by laboratory tests, are generally used for assessing the nature & quality of fuel shown. (see Table 2)

Table 2 The fuel properties

Properties	Fuel Oils		
	Furnace Oil	LS.H.S.	L.D.O.
Density (Approx. g/cc at 15°C)	0.89–0.95	0.88–0.98	0.85–0.87
Flash Point (°C)	66	93	66
Pour Point (°C)	20	72	18
G.C.V. (kCal/kg)	10,500	10,600	10,700
Sediment, % Wt. Max.	0.25	0.25	0.1
Sulphur Total, % Wt. Max.	Up to 4.0	Up to 0.5	Up to 1.8
Water Content, % Vol. Max.	1.0	1.0	0.25
Ash % Wt. Max.	0.1	0.1	0.02

It can be hazardous to store furnace oil in barrels. A better practice is to store it in cylindrical MS tanks, either above or below the ground. Furnace oil, that is delivered, may contain dust, water and other contaminants.

The sizing of storage tank facility is very important. A recommended storage estimate is to provide for at least 10 days of normal consumption. Industrial heating fuel storage tanks are generally vertical mild steel tanks mounted above ground. It is prudent for safety and environmental reasons to build bund walls around tanks to contain accidental spillages.

As a certain amount of settlement of solids and sludge will occur in tanks over time, cleaning should be carried out at regular intervals-annually for heavy fuels and every two years for light fuels. A little care should be taken when oil is decanted from the tanker to storage tank. All leaks from joints, flanges and pipelines must be attended at the earliest. Fuel oil should be free from possible contaminants such as dirt, sludge and water before it is fed to the combustion system. Piping MS ERW / Seamless, class B is used for fuel Oil & C class is used for gas flow. Heating of oil is required in case heavy oil is used. Recommended heating with the flameproof storage tank heater is up to 55ºC. The service or day tank is used for daily use near the furnace is also require Non-flameproof heater with recommended heating up to 55ºC. Before firing, flexible MS oil pipe used for heavy oil is to be opened & cold oil to be drained until hot oil appears for startup.

2.4 Combustion

The process of burning is called combustion. Combustion is a chemical reaction of hydrocarbon fuel & atmospheric air (Mainly oxygen is responsible for ignition) in presence of flame/spark. In Industrial Furnace, Combustion system (Heart of the Furnace) comprises Burner, Blower Heating & Pumping unit, Gas Train, Oil & gas control valves, Air control valves with necessary piping is used for combustion in the combustion chamber. Combustion is divided into two main categories. i. Complete combustion ii. Incomplete combustion.

$$\text{Complete combustion}: \quad CH_4 + 2O_2 \longrightarrow CO_2 + 2H_20 + \text{energy} \tag{1}$$

$$\text{Incomplete combustion}: \quad 4CH_4 + 7O_2 \longrightarrow 2CO + 2CO_2 + 8H_20 \tag{2}$$

Complete combustion means complete burning of fuel with CO_2 formation. Incomplete combustion forms CO in the exhaust flue gases which are hazardous leads to pollution in the atmosphere [5]. Incomplete combustion also releases heat but leads to pollution in the atmosphere. This amount of energy released is used for heating the charge to desired degree for further applications. The efficiency of a boiler or furnace depends on efficiency of the combustion system. The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur etc. This amount of air is called stoichiometric air. For ideal combustion process for burning one kg of a typical fuel oil containing 86% Carbon, 12% Hydrogen, 2% Sulphur, theoretically required quantity of air is 14.1 kg. This is the minimum air that would be required if mixing of fuel and air by the burner and combustion is perfect. The combustion products are primarily Carbon Dioxide (CO_2), water vapor (H_2O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air [6].

After surrendering useful heat in the heat absorption area of a furnace or boiler, the combustion products or fuel gases leave the system through the chimney, carrying away a significant quantity of heat with them. For complete combustion of everyone kg of fuel oil 14.1 kg of air is needed. In practice, mixing is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel oil. If too much air than what is required for completing combustion could enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses. Less air would lead to the incomplete combustion and smoke. Hence, there is an optimum excess air level for each type of fuel. The burner is the principal device for the firing of fuel. The primary function of burner is to atomize fuel to millions of small droplets so that the surface area of the fuel is increased enabling intimate contact with oxygen in air. The finer the fuel droplets are atomized; more readily will the particles meet the oxygen in the air and burn.

The objective of good combustion is to release all the heat in the fuel [7]. This is accomplished by controlling the "three T's" of combustion which are (1) Temperature high enough to ignite and maintain ignition7of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time enough for complete combustion. The efficiency of a boiler or furnace depends on efficiency of the combustion system. The amount of air required for complete combustion of the fuel depends on the elemental constituents of the fuel that is Carbon, Hydrogen, and Sulphur. This amount of air is called stoichiometric air. For ideal combustion process for burning one kg of a typical fuel oil containing 86% Carbon, 12% Hydrogen, 2% Sulphur, theoretically required quantity of air is 14.1 kg. This is the minimum air that would be required if mixing of fuel and air by the burner and combustion is perfect. The combustion products are primarily Carbon Dioxide (CO_2), water vapor (H_2O) and Sulphur Dioxide (SO_2), which pass through the chimney along with the Nitrogen (N_2) in the air.

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2.5 Stoichiometric air

The amount of main constituents in the furnace oil at lab analysis by weight: Carbon (85.9%), Hydrogen (12%), Oxygen (0.7%). Nitrogen, sulphur, Water & Ash are less than 0.5%. Gross calorific value is 10880 Kcal/kg [9]. Ex. Consider a sample of 10 Kg of Furnace oil, Calculate the theoretical air required. (see Figure 1, Table 3)

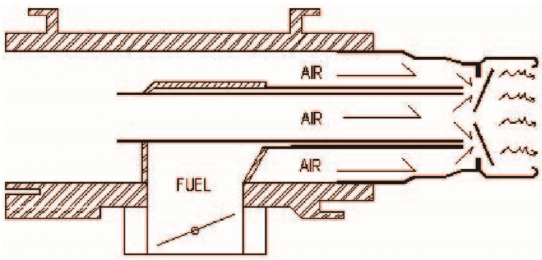

Figure 1 Burner

Table 3 The chemical reactions

Element	Molecular Weight (Kg/Kg·mole)
Carbon (C)	12
Oxygen (O_2)	32
Hydrogen (H_2)	2
Sulphur (S)	32
Nitrogen (N_2)	28
Carbon dioxide (CO_2)	44
Water (H_2O)	18
Sulphur dioxide (SO_2)	64

$C+O_2 \rightarrow CO_2$

$12+32 \rightarrow 44$

12 kg of carbon requires 32 kg of oxygen to form 44 kg of carbon dioxide. => 1 kg. of carbon requires 32/12 i.e. 2.67 kg of oxygen. $85.9C + (85.9x2.67)O_2 \rightarrow 315.25CO_2$ $S+O_2 \rightarrow SO_2$

$32 +32 \rightarrow 64$

32 kg of sulphur requires 32 kg of oxygen to form 64 kg of sulphur dioxide. => 1 kg. of sulphur requires 32/32 i.e. 1 kg of oxygen.

$0.5S + (0.5x1)O_2 \rightarrow 1SO_2$

$2H_2 + O_2 \rightarrow H_2O$

$4+32 \rightarrow 36$

4 kg of hydrogen requires 32 kg of oxygen to form 36 kg of water.

=> 1 kg. of hydrogen requires 32/4 i.e. 8 kg of oxygen.

$12H_2 + (12\times8)O_2 \rightarrow (12\times9)H_2O$

Total Oxygen required for 100 kg = 229.35 + 96 + 0.5 = 325.85 kg

=> For 10 Kg = 32.58 kg

Oxygen already present in 10 kg of fuel = 0.07 kg.

=> Actual Oxygen required = 32.58 – 0.07 = 32.51 kg.

=> Quantity of dry air required = 32.51/0.229 = 141.96 Theoretical air required = 141.96/10 = 14.19 kg /kg of Furnace oil.

Volume of air required, 1.1 liters of Furnace oil weighs 1 kg & generates 44000 BTU (British Thermal Unit) heat unit after complete combustion.

Air requirement in CFH (Cubic Feet per Hour)

CFH of air = BTU / 100 = 44000/100 = 440 CFH of air.

Hence 1 kg of furnace oil requires 440 CFH of Air.

Practically complete combustion is not possible & hence excess air about 20% is always used & included in above quantity. i. e. 440 + 88 = 528 CFH of air is considered.

Hence 1 kg of furnace oil requires 528 CFH of Air [10,11].

2.6 Refractories

Refractories are materials which withstand high temperature & do not fuse even at a very high temperature. These are used in brick form for building up furnace wall, roof, hearth, door & chimney duct through which flue gases are escaped into the atmosphere. (see Table 4 and 5)

Table 4 The classification based on refractoriness

Type	Refractoriness / Fusion Point, ºC
Low heat duty (LHD)	1520 – 1630
Medium heat duty (MHD)	1630 – 1670
High heat duty (HHD)	1670 – 1730
Super heat duty (SHD)	> 1730

Table 5 Firing temperature of some common bricks

Refractory Type	Firing Temperature ºC
Fireclay Bricks	1250 – 1440
High Alumina Bricks	1450 – 1550
Silica Bricks	1450 – 1510
Chrome Bricks	1450 – 1650
Silicon Carbide Bricks	1370 – 1510

Requisites of Good Refractory:

(1) Conserve heat & Prevent heat loss from the furnace.

(2) Withstand high temperature to which it is exposed.

(3) Withstand sudden change in temperatures.

(4) Contraction & expansion should be uniform.

(5) Withstand pressure which is likely to be put on it.

(6) Resistant to cutting action of flue gases & Flames.

(7) Corrosion resistant to slag formation.

(8) Crushing strength is very important in furnace technology as it varies with temperature. Ordinary fire-clay bricks which has crushing strength as 950 kg/cm^2 when cold at 20ºC and reduction to 555 kg/cm^2 at 800ºC.

(9) Refractoriness is resistance to fusion of the refractory under a steady rise in temperature.

Fire clay bricks are the most commonly used refractories due to their cheapness & can be heated to a very high temperatures even though their thermal conductivity is low. It has excellent resistance to thermal fatigue. These bricks are used for flues, chimney lining, steel castings, cements, glass melting & many applications.

Specially made high Alumina refractory block (60% or 90% Alumina) is placed around the burner nozzle to withstand flame temperature as well as guide the flame in the combustion chamber. The most common cause of failure of refractories is chemical reaction with the environment in which it is worked. Attacks on refractory by metal or slag is unavoidable. It can be minimized by de-oxidation with aluminum metal [2].

Refractories used in furnaces:

(1) Blast Furnace – Super duty fire clay bricks for upper course & high duty in lower course are used.

(2) Cupola – Fireclay lining.

(3) Boiler furnaces – Fireclay bricks / High Alumina bricks.

(4) Rotary Kiln for cement - Fireclay bricks / High Alumina bricks / Magnesite bricks.

(5) Reheating Furnace – Fireclay bricks / Chrome Magnesite bricks.

(6) Glass Melting Furnace – Sillimanite bricks.

(7) Hot metal ladle – Fire bricks.

(8) Laboratory Furnaces – High alumina refractory lined with insulating bricks [2].

(9) Heat Treatment – Fire bricks / Insulation bricks / Ceramic Fiber.

(10) Pit type non-ferrous Melting – Crucible / CI Pot

(11) Reverberatory aluminum Melting – Fire bricks / Insulation bricks / high alumina bricks.

3 Conclusion

The research paper provides useful guidelines for the furnace Designer, Manufacturer as well as end user to run their furnace efficiently. Complete combustion of fuel & utilization of the heat input is required to Control Pollution, Global warming & Enhance Furnace Efficiency. Study of fuels, combustion & refractories in industrial furnace are important issues to understand how effectively this can be used to run the furnace efficiently. The research is carried out by using theoretical study of academic books, Journal papers, and literature of various furnace manufacturers. Observations are taken by practical working on industrial furnace and by feedback from the End users. Safety is the most important factor while considering any material for the Furnace.

This research work & study will be helpful to understand the proper use of fuels, refractories for long life of the furnace. The final goal is to help the furnace manufacturer & end user to design as well as run the furnace smoothly & efficiently [14].

Conflicts of interest

The authors declare that they have no conflict of interest.

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