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INTRODUCTION

Scope

This guideline provides a review of an ethylene / olefin furnace. With the existence this design guideline can give a way to engineers to understand basic design of olefin furnace with suitable size, material and heat of combustion. Furthermore, it also helps them to do the sizing of the olefin furnace by engineering calculations.

The choice of furnace and distributor design is crucial to give the best performance of furnace. For good performance of furnace is influenced by the maximum the heat absorbed and capacity of burner. In this section will calculate the burner, radiant, convection and stack design. Also tube in each section and efficiency of furnace..

The design of olefin furnace may be influenced by factors, including process requirements, economics and safety. In this section, there are tables that assist in making these factored calculations from the vary reference sources. All the important parameters use in the guideline are explained in the definition section which help the reader more understand the meaning of the parameters or the term used.

The theory section explained about section of the olefin furnace and how to calculate sizing and selecting the furnace. This guideline helps the reader to understand about combustion concept. The combustion is important thing in the furnace because it is a process basic needed in the olefin furnace. Besides that, material and heat balance is also important to knowing in the olefin furnace.

The application of the olefin furnace theory with the example will make the engineer easier to study for the olefin furnace and the ready to perform the actual design of the olefin furnace.

General Design Consideration

Olefin manufacturing is the third largest petrochemical industries after ammonia manufacturing and petroleum refining. Annual global production of ethylene is about 120 million tons with a continuous annual increase of some 4 - 5 %. Ethylene and propylene have no end use, they are building blocks for a large variety of chemicals and petrochemical products.

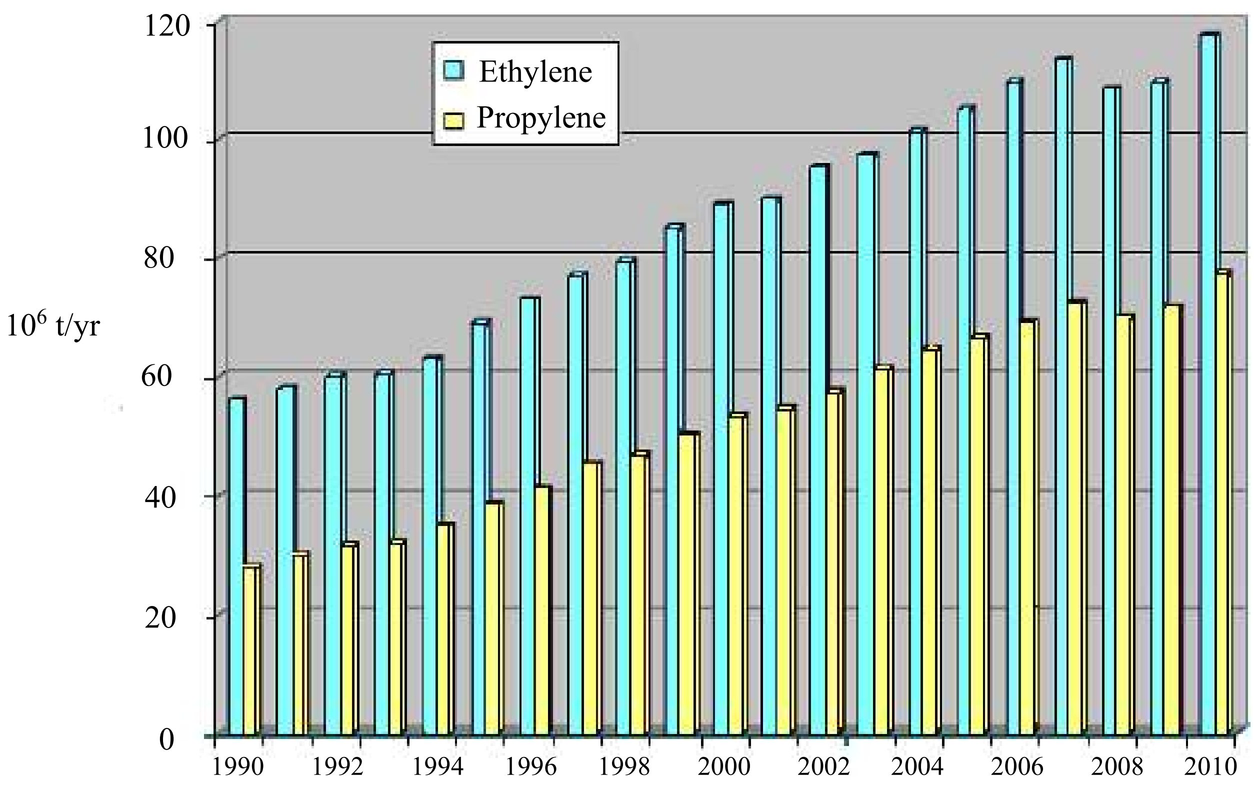

Figure 1: Global consumption of ethylene and propylene.

Olefins are produced by steam cracking of large hydrocarbon molecules to form a complex mixture rich in ethylene and other olefin gases, called pyrolysis. Pyrolysis is a gas-phase reaction at very high temperature. As the reaction is highly endothermic and requires high temperature, it is carried out in tubular coils within a fired furnace. A hydrocarbon mixture is heated in metal tubes inside a furnace in the presence of steam to a temperature at which the hydrocarbon molecules thermally decomposes

The cracking reactions are divided into primary and secondary reactions. Primary reactions involve the breaking down of large molecules of high hydrocarbon feedstock to form free radicals, then recombine to form new molecules (olefins: ethylene, propylene, and butadiene). This process is depending on the reaction temperature, time and predominantly on the highest reaction temperature or the coil outlet temperature.

Then process is followed by secondary reactions in which the olefins combine to form larger molecules and hydrogen. The cracked effluent should be cool quickly to prevent undesirable secondary reactions from taking place. Typical furnace cracking coil reaction time is 0.15 – 0.2 second and quenching is started within 0.01 second after leaving the reaction zone. The combine in secondary reaction is affected by the partial pressure of hydrocarbon. Partial pressure can be thought of as a combination of the steam ratio and the total reaction pressure.

Lowering steam ratio or increasing the coil outlet pressure reduces the ethylene yield but propylene is not affected. Thus the main control on product yield distribution is by varying the coil outlet temperature. The secondary reactions become more significant with the higher temperature and olefin partial pressure. Besides degrading the desirable olefin products, the secondary products can also lead the production of coke. Figure 2 is described the process reactions.

Initation

$$C_2H_6 \xrightarrow{K_1} CH_3^* + CH_3^*$$

Hydrogen abstraction

$$CH_3^* + C_2H_6 \xrightarrow{K_2} CH_4 + C_2H_5^*$$

$$H^* + C_2H_6 \xrightarrow{K_3} H_2 + C_2H_5^*$$

Radical decomposition

$$C_2H_5^* \xrightarrow{K_4} C_2H_4 + H^*$$

Termination

$$H^* + H^* \xrightarrow{K_5} H_2$$

$$H^* + CH_3^* \xrightarrow{K_5} CH_4$$

$$H^* + C_2H_5^* \xrightarrow{K_5} C_2H_6$$

$$C_2H_5 + CH_3^* \xrightarrow{K_5} C_3H_8$$

$$C_2H_5^* + C_2H_5^* \xrightarrow{K_5} C_4H_{10}$$

Figure 2: Process cracking

An industrial pyrolysis furnace is a complicated piece of equipment that functions as both a reactor and high-pressure steam generator. Pyrolysis furnace section consists of four furnaces for cracking fresh and recycles feed. Each furnace has two independently fed and controlled radiant boxes which share a common convection section. Burners are arranged on the walls and on the floor of the firebox for indirect firing. The firing is by gas fuels only.

This section is called the radiant section because the radiant heat is recovered. The draft for the furnace is provided by an induced draft fan located on each furnace. The pyrolysis reactions proceeds in tubular coils made of Cr/Ni alloys. These coils are hung vertically in a firebox. Depending of furnace design, there may be between 16-128 coils per firebox.

At the end of the pyrolysis, the reaction needs to be quenched rapidly to avoid further decomposition of the desired olefins. This is achieved by either indirect cooling using a quench exchanger or direct cooling by injecting quench oil into the gas effluent. Each furnace system is fitted with cracking effluent quench exchangers for heat recovery in the form of super high pressure (SHP) steam.

Each furnace has four modules of selective linear exchangers (SLE), and each module containing 16 SLE’s. The process streams from each SLE module are collected in a collection header. The cracked effluent is collected from all the collection headers, and is then sent downstream to quench oil tower.

A steam drum is associated with furnace, mounted at a sufficient elevation above the selective linear exchanger (SLE) to provide boiler feedwater circulation on the shell side of the exchanger by thermosyphon action.

The heat carried by the flue gas is recovered at the convection section of the furnace. This section consists of a series of “tube banks” where the heat is recovered for hydrocarbon preheat, a boiler feedwater economizer, hydrocarbon plus dilution steam which is staged in two banks, super high pressure steam superheating, and dilution steam superheating.

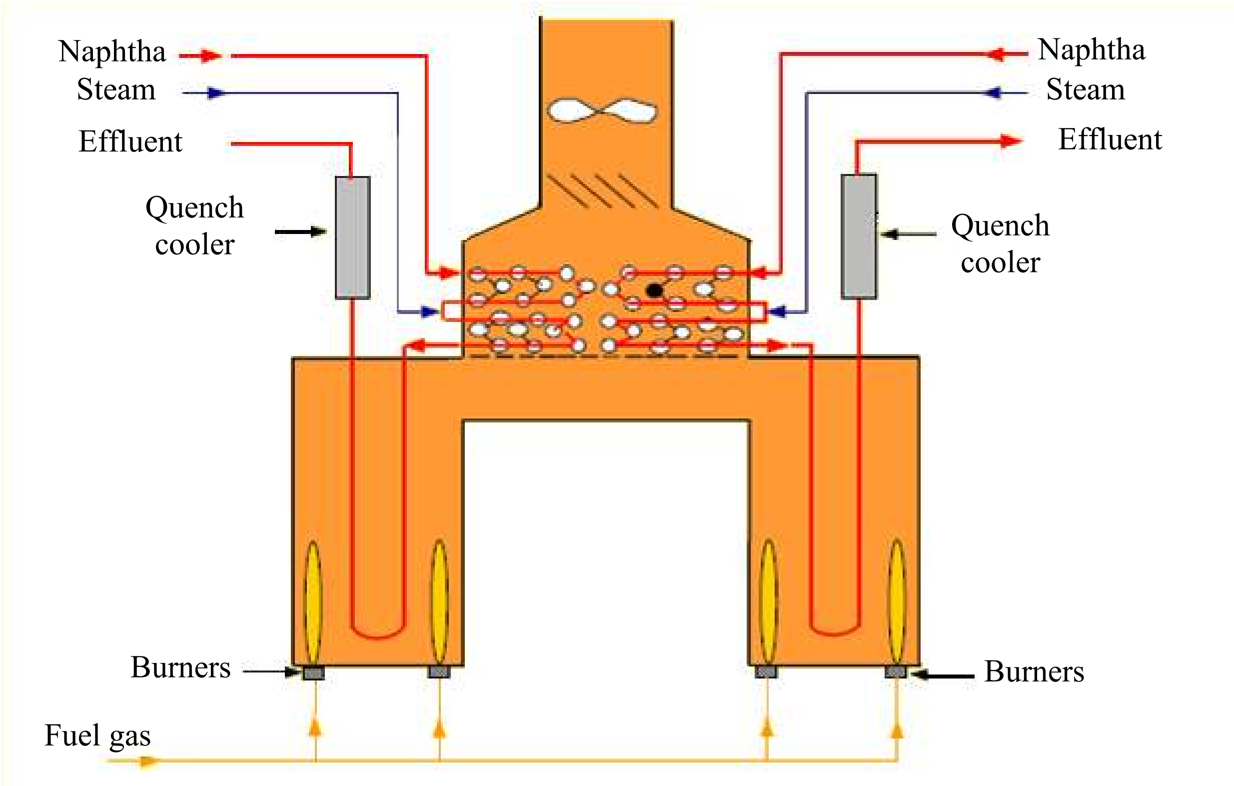

Figure 3: Olefin furnace layout

The process flow through the convection section, radiant coils and associated SLE's has two independently controlled, segregated flow paths or zones. The selected vapor or liquid hydrocarbon feed flow is controlled by a separate flow control valve for each flow path. Each selected flow path has an associated radiant box zone and the fuel gas firing for each radiant box zone is independently controlled. Thus through the distinct process flow paths and controls incorporated into the furnace.

Hydrocarbon feed selected from either the liquid or vapor feed header enters the selected furnace zone which is controlled by parallel control valves flow through the hydrocarbon preheat bank in the furnace convection section, then split into 3 phases. Each zone feed has a distinct and independent source of superheated dilution steam.

For liquid feeds, this bank preheats the feed to a temperature where it can be completely vaporized when mixed with the superheated dilution steam. While vapor feeds, the preheat bank provides sensible heat duty to the feed before being mixed with the superheated dilution steam. Three passes from the hydrocarbon preheat bank on each end of furnace are combined and routed to a mixing tee.

Each furnace has two hydrocarbon/dilution steam mixing tees, one on each end of the convection section for each zone feed to ensure complete hydrocarbon vaporization by thoroughly mixing the hydrocarbon zone feed with superheated dilution steam.

The hydrocarbon/dilution steam from each mixing tee is then split into three passes to the first of two hydrocarbon/steam banks, once again maintaining the distinct feed zones. The six hydrocarbon/steam passes, three passes on each side of the convection section for each feed zone, are combined in two mixing headers, one mixing header per feed zone. The hydrocarbon/steam mixture is then split into 4 passes, two passes from each mixing header for each feed zone, and is further routed into the second hydrocarbon/steam bank located just below the dilution steam bank. The hydrocarbon/steam banks heat the hydrocarbon/dilution steam mixture to a temperature just below that where cracking begins.

The two passes of the second hydrocarbon/steam bank are combined on each end of the convection box and routed to a mixing fitting, maintaining the separate zone feeds. The mixing fitting provides complete mixing of the hydrocarbon/steam ensuring a uniform mixture temperature entering the radiant section of the furnace.

Hydrocarbon/steam from each feed zone exiting the mixing fitting is split into two lines, each line feeding two radiant coil distribution manifolds. Each of the eight distribution manifolds (four on each side of the convection section) feed eight radiant coils via critical flow venturies in each radiant coil inlet. As long as the absolute pressure ratio is maintained at 0.85 or less across the venturi nozzle, constant flow to each radiant coil is ensured, regardless of downstream pressure changes.

A pyrolysis furnace should be moved in the direction of short residence time, low hydrocarbon pressures and high temperatures for optimum production of ethylene from any feedstock. The process chemistry review reveals at least three design requirements:

1. Low Pressure. Any time the moles of products are larger than the moles of reactants the equilibrium favors low pressures. Modern furnaces operate under low pressure of 175-240 kPa. The required compressor horsepower becomes very large to achieve lower coil outlet pressure,.
2. Low Hydrogen Partial Pressures. To reduce the unwanted hydrogenation reaction, lower hydrogen partial pressures would produce more of the desired products.
3. Short Residence Time. To reduce the unwanted condensation reaction, shorter residence times would produce more of the desired products. In order to reduce the residence time, engineers have designed radiant tubes of smaller diameters, better metallurgy and burners that are more efficient. Modern cracking furnaces operate in residence time range between 0.08-0.25 s. Tube diameter has reduced to the range of 25.4 – 101.6 mm (1-4 in).
4. Inert. Dilution steam is an inert that premixed with hydrocarbon feed before feeding to the pyrolysis coils. Dilution steam was added then forth to reduce coking and carburization. Also to lower the hydrocarbon partial pressures. The mass ratio of steam to hydrocarbon feed is 0.3 for ethane feed to 0.6 for gas oil cracking. It is a controlled parameter in furnace operations.

5. High temperature. Pyrolysis is a highly endothermic reaction. The operating temperature of pyrolysis furnace is the region of 750 – 900^{o}C. The downside of higher operating temperature is more rapid coking rate and carburization, which shortens the tube-life.

Table 1: Typical Residence Times Yields for Light Naphtha

Residence Time (seconds)	0.1	0.2	0.5
Methane	15.48	15.78	16.16
Ethylene	34.16	32.16	29.37
Propylene	17.02	17.35	17.78
Butadiene	5.2	5.1	5
Benzene	5.89	6	5.75
Toluene	2.59	2.65	2.52
Fuel oil	3.12	3.35	3.61

The pyrolysis reactions are endothermic and time dependant reactions. The flame pattern and the resulting heat flux can have the net effect of changing the effective length of the coil. The heat flux should be uniform; if the heat flux is not uniform the coil effective length can be reduced. If heat flux is not uniform hot areas can cause over cracking and shorting coil life. The shape of the flame is determined by burner designers according to heat input requirements by the technology provider. The shape of the fire box will affect the flame pattern and heat flux. Deviation from rectangular has not proved to be successful.

In a typical ethylene furnace the pyrolysis reaction is endothermic. For this reason, furnace tube material must be suitable to accommodate the high process temperature. Continual improvement of furnace tube materials and furnace design has made it possible to accommodate 750 – 850°C and up to 900°C or even higher. The tubular coils within an industrial pyrolysis furnace are usually made of the base Cr/Ni alloys and grow in popularity.

Cr/Ni alloys for furnace tubes are selected for their better cocking erosion resistance, high creep strength, carburization resistance, ductility, and thermal shock resistance. Furnace tube are usually produced of the following steel grades 304L, 316, 321, 304H, 347H (formally stabilized at 1650 °F for 4 hours - preferred if it can be done internally at the mill), 317L, 2205.

There are 4 types of furnace coils; Single pass, U coil, W coil, and Hybrid coil. If short residence time is considered the single most important objective, then a short coil with tubes of small diameter will be considered. If a combination of high capacity, medium resident time and low hydrocarbon partial pressure is judged to be most beneficial, then a relatively larger tube will result. Below is discussed each coil.

Single Pass

Single pas has short residence time, one pass of uniform size, and fire box floor to roof orientation. In single pass, the cracking furnace produces the highest olefin conversion due to short residence time and downstream separation section can be smaller. The advantages of single pas:

1. Simple, Robust Design with short, straight radiant tubes
2. Larger diameter radiant tubes
3. Primary Quench Exchangers do not require mechanical cleaning
4. Produces 6% to 8% higher C2H4yield
5. Requires a smaller, less expensive plant
6. Consumes less energy per ton of ethylene
7. Larger Diameter Radiant Tubes

8. Enhanced Tube Materials
9. Higher design temperature for crossover piping, allowance made for incipient cracking in convection coils
10. Use of Critical Flow Venturis for Flow Distribution
11. Inlet Manifold Allow Access to Tubes from Outside the Firebox
12. Venturis can be removed for cleaning without cutting, welding, x-ray of welds
13. Maximum Selectivity -produce the highest ethylene yields and maximum olefins selectivity for all feeds at any severity
14. Online decoking feature to extend run times without significant loss of production
15. Coil quench exchanger has established reliable system, many units in operation. Metallurgy of quench exchanger is very important and should be sodium stress corrosion resistant

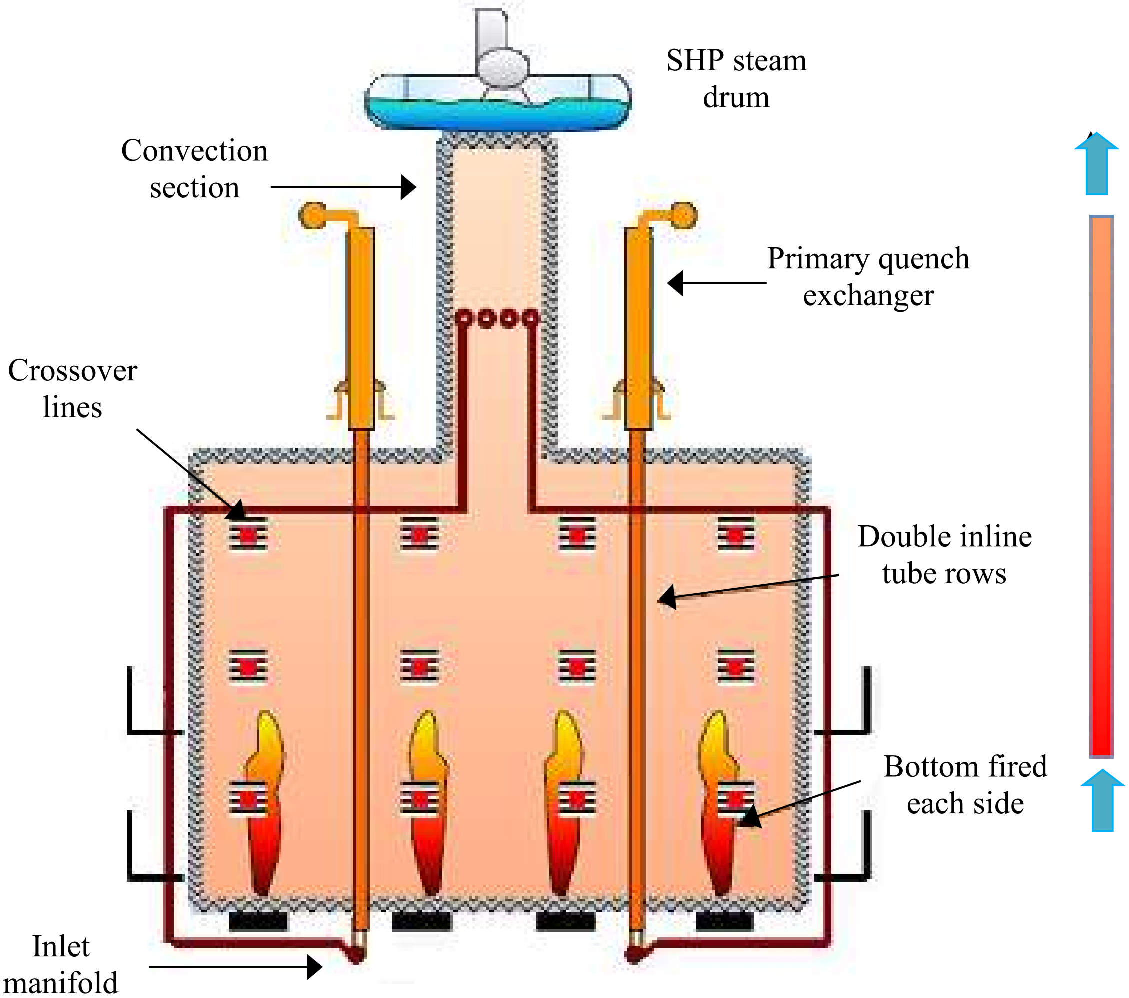

Figure 4: Typical end view single pass

U Coil / U Sweep Bends/ Two Pass

U coil has one or more passes of uniform size and U configuration fire box roof to roof orientation. U coil has some advantages:

1. Moderate Olefin Conversion
2. Operations Friendly
3. Dilution Steam and Feed tolerant
4. Moderate coil life
5. Moderate Thermal shock
6. Coil quench exchanger has established reliable system, many units in operation. Metallurgy of quench exchanger is very important and should be sodium stress corrosion resistant

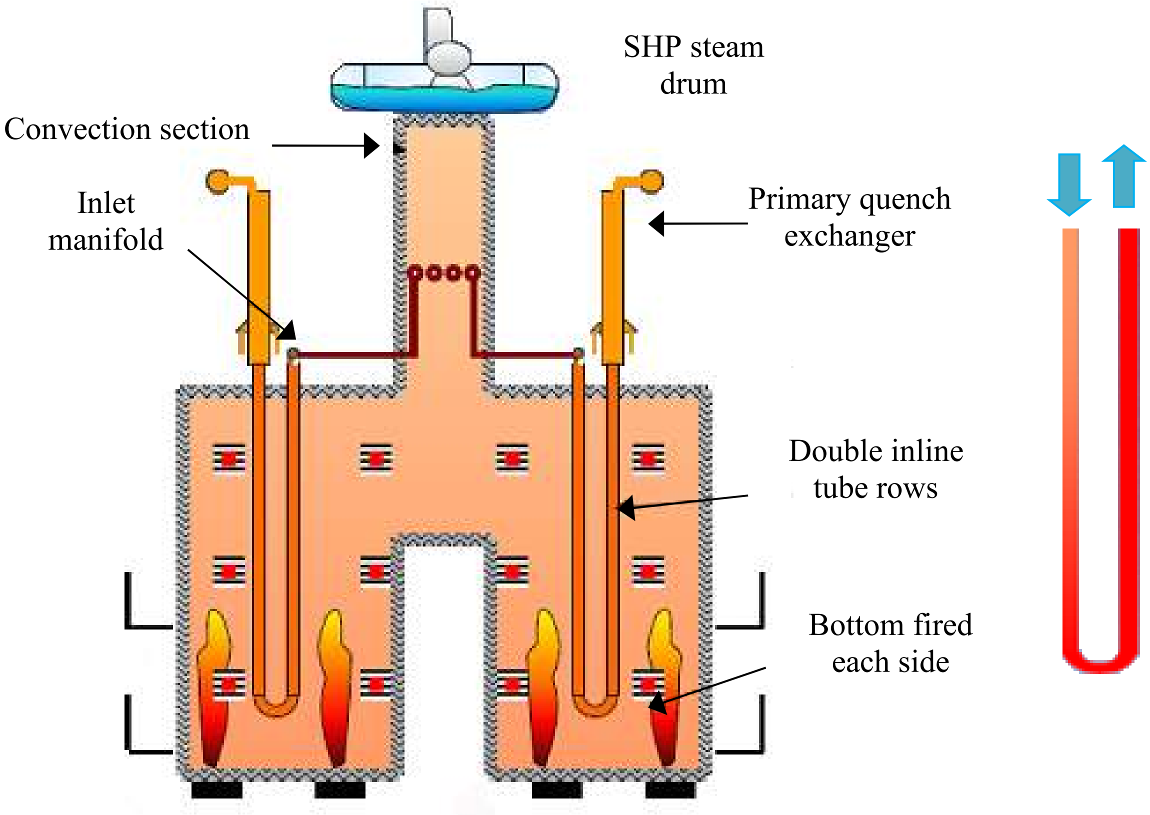

Figure 5: Typical end view two pass

Coil / W Sweep Bends / M Coil

W coil has one or more pass of increasing size and W configuration fire box roof to roof orientation. It is good run length between decokes, good coil life and moderate thermal shock. Coil quench exchanger has established reliable system, many units in operation. Metallurgy of quench exchanger is very important and should be sodium stress corrosion resistant

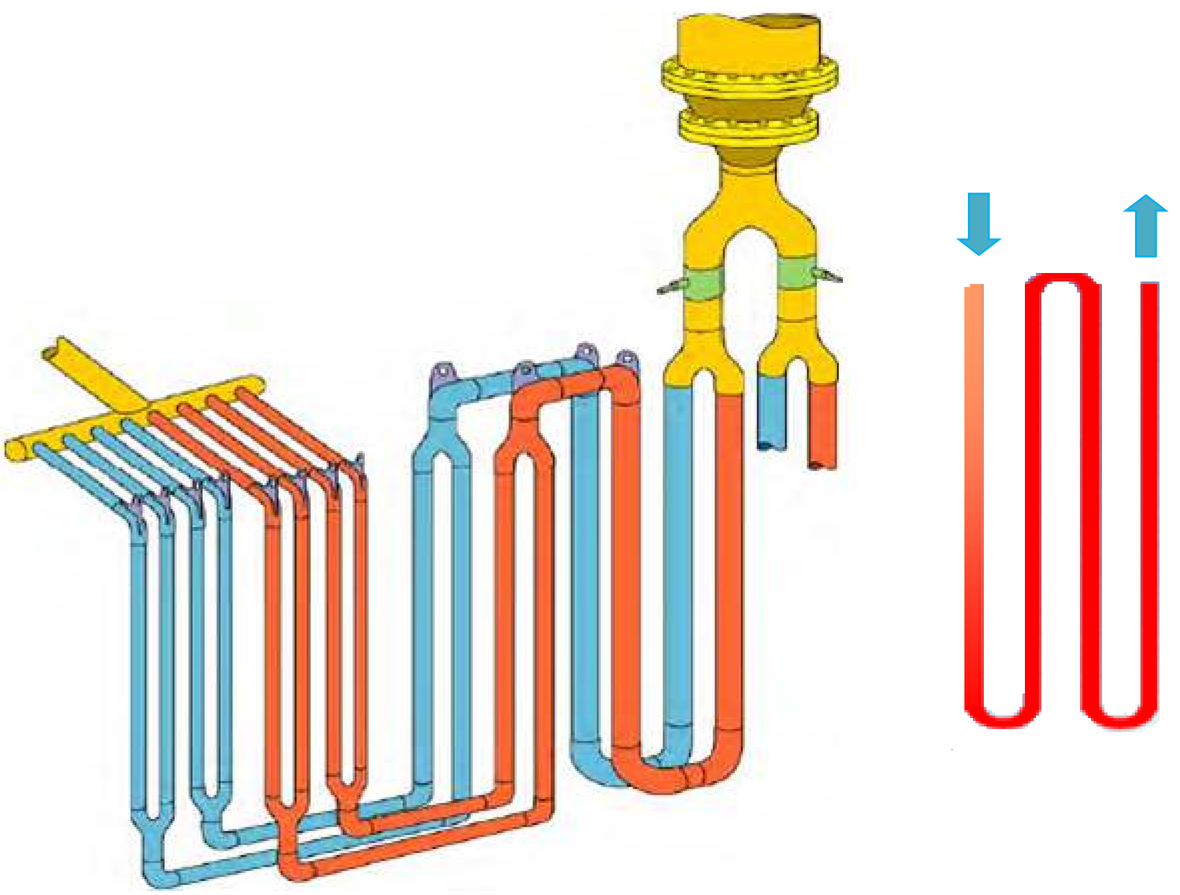

Figure 6: W Sweep Bend coil configuration

Hybrid Coil

Hybrids coil has one or more passes of increasing size and fire box roof to roof orientation. Hybrid coil has some advanteges:

1. Good run length between decokes
2. Good coil life
3. Good Thermal shock
4. Dilution Steam and Feed tolerant
5. Coil quench exchanger is recently changed system to reduce residence time. Metallurgy of quench exchanger is very important and should be sodium stress corrosion resistant.

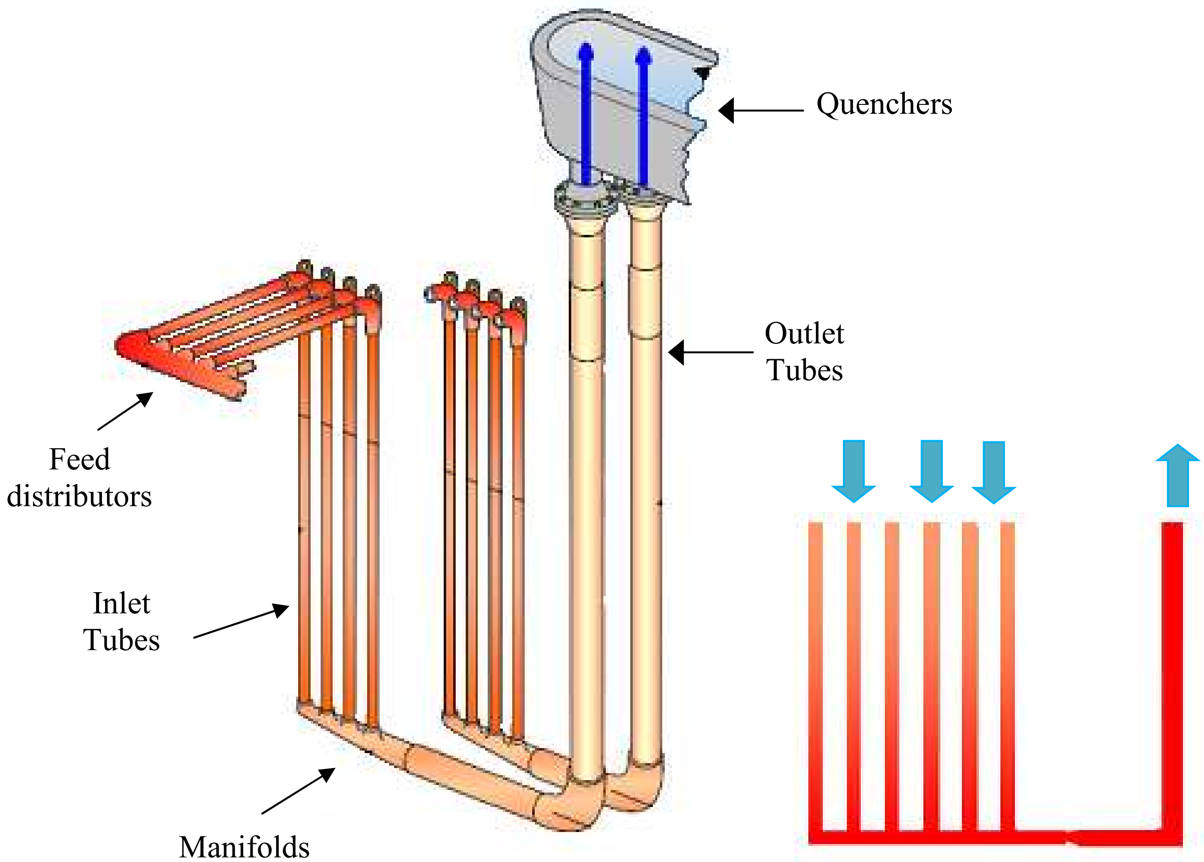

Figure 7: Hybrid coil configuration

Table 2: The different of coils type

	Size	Residence time (seconds)	Design run length on naphtha (days)	Design decoke time (hours)
Single pass	1 in by 40 ft	0.08 – 0.12	30 – 35	18 – 24
U coil	2 in by 80 ft	0.20 – 0.25	35 – 45	24 – 30
W sweep bends	4 in by 120 ft	0.35 – 0.45	45 – 60	30 – 36
Hybrid coil	2 – 6 in by 80 ft	0.20 – 0.25	35 – 45	24 – 30

Below is design guideline generally for olefin furnace and will discussed deeper in theory section.

1. Steam may be added to the fuel gas to reduce the NOx emissions. This steam has been shown to even the heat flux distribution resulting in higher yields and run lengths.
2. A short coil with tubes of small diameter will be considered If short residence time is the single most important objective.
3. A larger tube should be used If a combination of high capacity, medium resident time and low hydrocarbon partial pressure is judged to be most beneficial.
4. The quantity of dilution steam required is dependent upon the feedstock selected; lighter feed stocks such as ethane require lower steam (0.2 Ib./Ib. feed), while heavier feed stocks such as naphtha and gas oils require steam/feed ratios of 0.5 to 1.0.
5. The dilution steam has the dual function of lowering the partial pressure of the hydrocarbon and reducing the carburization rate of the pyrolysis coils.
6. In a typical pyrolysis process, the steam/feed mixture is preheated to a temperature just below the onset of the cracking reaction, typically 650° C.

7. Generally the residence time in the pyrolysis coil is in the range of 0.2 to 0.4 seconds and outlet temperatures for the reaction are on the order of 700° to 900° C.
8. The flue gas temperatures in the radiant section of the fired heater are typically above 1,100° C.
9. Flue gas pressure inside the furnace shall be in between -0.5 mbarg and -1.0 mbarg
10. The exotic metal reaction tubes located in the radiant section of the cracking heater represent a substantial portion of the cost of the heater.
11. The operating of the exotic metal reaction tube should be as high ,and as uniform a heat flux and metal temperature as possible consistent with the design objectives of the heater. This will minimize the number and length of the tubes and the resulting total metal required for a given pyrolysis capacity.
12. In select heaters, radiant wall burners are installed in the top part of the sidewalls to equalize the heat flux profile in the top.
13. The firing rates in each radiant section may be separately controlled to provide the heat intensity, in each section, most suitable for the desired fluid processing conditions.
14. The typical profile shows a peak flux near the center elevation of the firebox, with the top and bottom portions of the firebox remaining relatively cold. In select heaters, radiant wall burners are installed in the top part of the sidewalls to equalize the heat flux profile in the top.
15. Some pyrolysis heater in which the first quarter or first half of a pyrolysis coil is provided with extended heating surface for increasing the adsorption of radiant heat. The extended heating surface may be on the inside or the outside of the tubes and typically is in the form of studs, fins or ribs.
16. Some pyrolysis heater in which vertical tubes in the radiant section are provided in a plurality of parallel rows, with each row being in a plane perpendicular to a plane through the longitudinal axis of the convection section of the heater.
17. Pressure upstream of the nozzles depends on the load of the furnace, increasing pressure downstream of the laval nozzles indicates increasing coke formation in the radiant coils; pressure ratio outlet/inlet must not exceed 0.90

18. Increasing Pressure upstream of TLE´s with constant load of the plant and constant suction pressure of the cracked gas compressor indicates an increasing coke formation in the TLE´s

19. With sudden change of fuel gas composition changing the heating value the COT is being kept constant by regulating the fuel gas pressure. The air shutters of the burners and the draft of the furnace have to be adjusted to guarantee a complete combustion, and not to exceed the O_2 surplus in the flue gas

DEFINITIONS

Bridgewall Temperature - The temperature of the flue gas leaving the radiant section

Burner – Equipment wher the gas or fuel oil is delivered and burned to produce heat.

Coil - A series of straight tube lengths connected by 180^{o} return bends, forming a continuous path through which the process fluid passes and is heated.

Coke - Solid residue remaining after certain types of coals are heated to a high temperature out of contact with air until substantially all components that easily vaporize have been driven off.

Convection Section - The portion of a heater, consisting of a bank of tubes, which receives heat from the hot flue gases, mainly by convection.

Combustion - the oxidation of a mixture of fuel and air. Terms of combustion will take place perfectly when time, temperature and turbulence.

Cracking - The process whereby complex organic molecules such as kerogens or heavy hydrocarbons are broken down into simpler molecules such as light hydrocarbons, by the breaking of carbon-carbon bonds in the precursors.

Crossover - Piping which transfers the process fluid either externally or internally from one section of the heater to another.

Damper - A device to regulate flow of gas through a stack or duct and to control draft in a heater.

Dilution steam – Steam which is added to reduce the partial pressure of hydrocarbons. This is done to aid the reaction to proceed in the forward direction to get desired products as per Le Chatlier's principle.

Draft - The negative pressure (vacuum) at a given point inside the heater, usually expressed in inches of water.

Excess Air - The percentage of air in the heater in excess of the stoichiometric amount required for combustion.

Endothermic - A process or reaction that absorbs heat, i.e. a process or reaction for which the change in enthalpy, ΔH, is positive at constant pressure and temperature

Fire Box - A term used to describe the structure which surrounds the radiant coils and into which the burners protrude.

Flue Gas - A mixture of gaseous products resulting from combustion of the fuel.

Fired Heater Efficiency - The ratio of heat absorbed to heat fired, on a lower heating value basis.

Heat Available - The heat absorbed from the products of combustion (flue gas) as they are cooled from the flame temperature to a given flue gas temperature.

Heat Duty - The total heat absorbed by the process fluid, usually expressed in MBtu/hr

Hydrogen abstraction - Any chemical reaction in which a hydrogen free radical is abstracted from a substrate

Lower Heating Value (LHV) - The theoretical heat of combustion of a fuel, when no credit is taken for the heat of condensation of water in the flue gas.

Naphtha - Any of several highly volatile, flammable liquid mixtures of hydrocarbons distilled from petroleum, coal tar, and natural gas and used as fuel, as solvents, and in making various chemicals.

Net Fuel - The fuel that would be required in the heater if there were no radiation losses.

Olefin - Any of a class of unsaturated open-chain hydrocarbons such as ethylene, having the general formula C_nH_{2n}; an alkene with only one carbon-carbon double bond.

Pyrolysis - A gas-phase reaction at very high temperature. As the reaction is highly endothermic and requires high temperature, it is carried out in tubular coils within a fired furnace.

Radiant Section - The section of the fired heater in which heat is transferred to the heater tubes primarily by radiation from high-temperature flue gas.

Shield Section - The first two tube rows of the convection section.

SLE exchangers - Double pipe exchangers consisting two sections, or legs in series, with the process stream in the inner pipe and the boiler feedwater/steam in the outer annulus.

Stack - A cylindrical steel, concrete or brick shell which carries flue gas to the atmosphere and provides necessary draft.

Stack Effect - The difference between the weight of a column of high-temperature gases inside the heater and/or stack and the weight of an equivalent column of external air, usually expressed in inches of water per foot of height.

Stack Temperature - The temperature of the flue gas as it leaves the convection section, or air preheater directly upstream of the stack.

Steam cracking - High-temperature cracking of petroleum hydrocarbons in the presence of steam.

Steam System – the system which is to generate super high pressure

NOMENCLATURE

A_r	Radiant surface area, ft^2
Cp_{air}	Specific heat of air, btu/lb F
Cp_{fuel}	Specific heat of fuel, btu/lb F
CtC/Do	Ratio, CtC/Do
Di	Tube diameter, in
Do	Tube outside diameter, in
Eff	Furnace Efficiency,%
EPA	Effective plane area, ft^2
G_f	Flue gas rate, lb/hr
G_{fuel}	Fuel flow required, lb/hr
G_{air}	Air flow required, lb/hr
H_a	heat input in the form of sensible heat of air, btu/lb fuel
H_f	heat input in the form of sensible heat of fuel, btu/lb fuel
LHV	Lower heating value of fuel, btu/lb fuel
L_{tube}	Tube length, ft
N_{tube}	Number of tube
$\%Q_r$	Radiation losses, %
$\%Q_{rabs}$	%radiant absorbed, %
Q_{comb}	Heat combustion, btu/hr
Q_s	Stack heat loss, btu/lb fuel
Q_r	Radiant heat loss, btu/lb fuel
Q_{in}	Heat input, btu/hr
Q_{abs}	Heat absorbed, btu/hr
Q_{rduty}	Heat radiant duty btu/hr, ft^2
Q_{rabs}	Radiant heat absorbed, btu/hr
Q_{rf}	Flux rate, btu/ft^2
Q_{conv}	Heat in convective zone, btu/hr
T_{flue}	Flue gas exit temperature, F
T_{air}	Combustion air temperature. F
T_{fuel}	Fuel gas temperature, F
T_{in}	Fluid in temperature, F
T_{out}	Fluid out temperature, F
TWT_{avg}	Tube wall temperature average, F

T_f	Pseudo firebox temperature, F
T_{fb}	firebox wall temperature, F
T_{us}	Unshielded firebox walls temperature, F
T_{sh}	Shielded wall temperature, F
T_c	convection temperature, F
X	Excess air, %

Greek Leters

α	Effectiveness factor

Superscript

BWT	Bridge wall temperature, F
PA	Plane area, ft^2
T	Temperature, F