Efficient Energy Conversion of Wastes and Fuels in Power Systems

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Abstract

Efficient fossil energy use with low pollution in all kinds of power plants is of growing interest in all industrial sectors. The use of energy is growing steadily by many countries worldwide due to the greater desire for enhancing better standards of living and to increase productivity. Efficient energy use is favorable for better productivity product quality, costs, and quality of human life but the energy use adversely impacts our environment. During the past decade energy demands from China and India have grown significantly and is projected to grow even more in the coming decades as they enhance their living standards and productivity. This clearly requires close examination of the available methods of fossil fuel energy conversion as well as advanced methods that will provide increased efficiency and pollution reduction. This section, after brief review on historical perspectives on energy conversion, provides a short review on the various methods used for energy conversion in industrial power plants as well as new innovative methods that are now beginning to become available with significant fuel saving, compact size of the equipment and low pollution. As an example, high temperature air combustion technology has seen wider acceptance of the technology in many kinds of industrial furnaces, in particular, for use in steel industry and fuel reforming furnaces with demonstrated energy savings of about 30% (on the average), about 25% reduction in the size of the equipment (compact size), about 50% reduction in low pollution and better quality of the product produced. Such significant energy savings were only dream of engineers in the past. This technology has been adapted by many countries worldwide. In addition advanced technologies are developed or being developed for use with coals (and solid fuels) since its cost based on energy content is low as compared to gaseous fuels, such as natural gas. Several commonly used methods in power generation are presented along with integrated and hybrid systems for increased efficiency. Clear representation is provided of the output energy available from known input energy. Some energy conversion techniques provide in-situ capture of pollutants while others must use air pollution control devices for pollution capture and/or pollution reduction prior to waste gases discharge to the atmosphere. The information provides quick guide on the commonly used methods of energy conversion in the USA and Europe, in particular when using solid fuels, such as coal. It is expected that future systems will be more energy efficient and emit even lower pollution via the use of combined cycle systems and integrated energy conversion systems. Advanced high temperature steam gasification results in hydrogen-rich syngas of higher heating value, reduced volume of the waste, and the remaining residue is clean and non-leachable.

Keywords: *Energy conversion, High temperature air combustion, Colorless distributed combustion, Energy efficiency, Waste to energy, Advanced waste to energy conversion*

1 Introduction

Energy conversion is one of the important issues to utilize the chemical energy contained in the fuel to the desired form of energy for the specified need [1-58]. This has been the prime theme (formerly also know as the heat/power engineering) for the numerous technological developments worldwide. The energy conversion deals with the conversion of energy (from such sources as fossil fuel, nuclear, biomass, various renewable and alternative energy sources) into desired and convenient usable form of thermal, mechanical, electrical to provide, among applications, of electricity, power, propulsion, transportation, heating and cooling. In some cases the chemical energy desired is of high energy density and desired octane/rating rating, while in other cases it is not of critical importance. But in all cases it must be environmentally benign and of high efficiency. In the earlier times the main focus was on increased power and not as much on efficiency and pollution, because of the relatively inexpensive costs of energy. However, the oil embargos of 70's, 80's and 2000's together with the limited earth's resources and observed global warming caused by the increased carbon dioxide in the atmosphere has caused greater awareness to engineers to develop environmentally benign energy and even more energy efficient devices. Innovative research and development efforts in an academic and research laboratory environment together with the entrepreneurial needs provide much of the availability of new products. In most cases the basic support has been provided by the federal funds which are then followed by industry for product development for specific product needs. Examples to support this include commercial aircraft engine development from military engines, automobile engines for increased fuel efficiency and flexibility with lower emissions, electric power from fossil, alternative and fossil fuels, micro-power generation for local use, portable electrical energy. Many times the budgetary issues on research and development efforts may impose an adverse effect on specific product development due to priorities on short term over long term issues. With the recent increased interest in energy, greater emphasis is placed on clean energy conversion from the limited fossil, alternative or nuclear energy sources. New as well as the more traditional energy conversion systems are being considered or reconsidered for increased efficiency and reduced pollution. A few examples include advanced designs for internal combustion engines, turbocharged engines, hybrid vehicles, combined cycle steam and gas turbine engines, advanced gas turbine cycle engines, fluidized bed combustors, advanced incinerators, coal gasification advanced power plants, zero emission power systems and miniaturized power systems. In fact we are living in a rapidly changing world that requires rapid continuous improvement of the old technology with the new one for efficiency improvement and reduced or sometime even negative environmental burden. Energy conversion is more complex, stimulating and viable field today than ever before because of the changed trend on the need for significantly increased efficiency and negligible environmental impact.

Although we have made much progress in the energy conversion system, there is no doubt that progress in the electronic industry has been significant during the immediate past 5 decades. Table 1 gives a direct comparison in the energy conversion sector and its comparison with the electronic sector during the past half 20th century. This table shows that although major advances have been made in both the areas the advances in electronic industry are more significant with laboratory on the computer chip using very large to super large scale integration so that the size of the system is much smaller and simultaneously provides much larger processing capability. In contrast the progress in energy/power industry has been primarily focused on larger scale units with high energy efficiency and lower pollution until the early 90's when a new concept of combustion was introduced, called High Temperature Air Combustion (called HiTAC), to provide simultaneous and significant benefits of energy conservation, lower emission (including NO_x, CO_2, unburned hydrocarbons, carbon monoxide, soot), compact size of equipment, near uniform thermal field in the entire burning zone to be called as an isothermal reactor and low noise emission levels.

Table 1: Major advances in electronics and energy industry during the last half of 20th century [7]

Decade	Electronics Industry	Energy/Power Industry
1950's	Vacuum tubes	High energy conversion
1960's	Transistors	Large scale units
1970's	Integrated circuits	Environmental pollution
1980's	Printed circuits and large scale integration	High efficiency
1990's	Very large scale integration	Higher efficiency, compactness, low pollution including, CO_2 and noise
2000+	Super large scale integration, compact and high density systems	Energy and environment conservation (zero emission) from variety of fuel sources

2 Brief History of Energy Conversion

Before proceeding to the major revolutionary method of energy conversion, it is appropriate to consider a few of the significant milestones on inventions and ideas on energy conversion. These are summarized in Table 2. It should be noted that the table does not include the entire history but only some major inventions so that a reader is referred to seek other references for gaining historical perspectives. Some of the omissions includes: V8 engine, ramjet, scramjets, rockets, space launch vehicles, microsatellites. The struggling efforts of many heroes on their ideas to produce practical hardware with the limited tools and resources available were quite challenging for producing machines for man and industry. In addition the fuels available for these machines were not as well defined as they are today. The progress on technology and industry was slow until the sound knowledge on thermodynamics became established in the 19th century. The development of the nuclear power was in the second half of the 20th century with the theoretical and experimental knowledge gained during the first half of the last century. The table reveals that fundamental R&D has made significant impact on the energy conversion needs in a range of areas for power, propulsion and transportation.

Table 2: Major significant invention milestones in selected energy conversion areas

Atmospheric engine using steam (first widely used heat engine)	Thomas Newcomen	1700
Steam condenser idea	James Watt Boulton and Watt steam engine	1765 (1775)
James Barber	Gas turbine idea patent	1791
Internal combustion engine invention using hydrogen / oxygen fuel mixture	Francois Isaac de Rivaz (Switzerland)	1807
Two-stroke engine patented 4 stroke engine operation	Nikolaus August Otto Nikolaus August Otto	1861 1876
Diesel fueled engine (patent issued)	Rudolf Diesel	1892 (1898)
Gas turbine Turbo jet idea (Patent issued)	Sir Frank Whittle	1929 (1932)
Turbo jet concept (Patent issued)	Hans Von Ohain	1933 (1935)
Turboprop idea for long range transports	Herbert Wagner	1934
Low heating value fuel combustion	F. Weinberg	1974
Regenerative combustion	Hotworks Combustion Technology Ltd	1985
High temperature air combustion	NFK Ltd and A. K. Gupta	1990
Green flame of hydrocarbon fuels	NFK Ltd and A. K. Gupta	1998

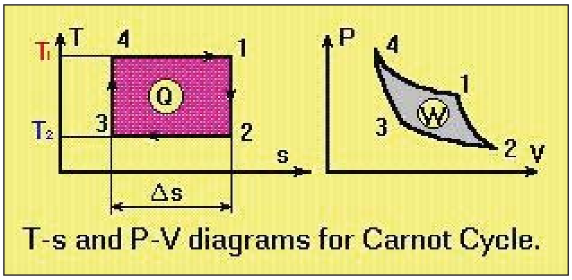


Figure 1: T-S diagram for the Carnot cycle.

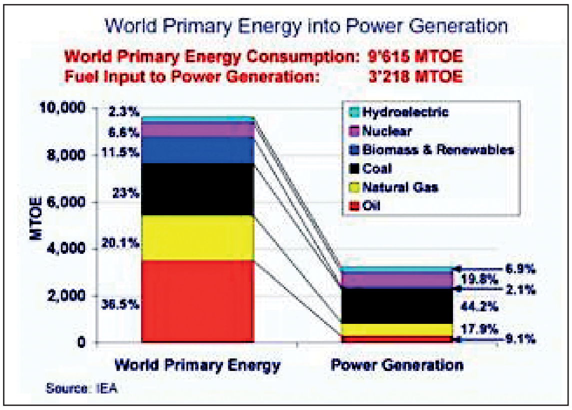
2.1 *Basic energy conversion concepts*

We now consider the basic concept of energy conversion using steam and air as the working media. The Rankine cycle is accepted as the basic standard for steam power plants. Before considering Rankine cycle we consider Carnot cycle as this cycle provides maximum possible efficiency. The ideal diesel cycle is a gas cycle and the Carnot cycle is a cycle for all fluids. The Carnot cycle provide the foundation of the second law of thermodynamics and the concept of irreversibility. The temperatures of the heat source and heat sink in this cycle provide thermal efficiency of a reversible cycle. Carnot cycle is hypothetical as one cannot build a reversible engine. Figure 1 shows Carnot cycle on a T-s diagram consisting of four processes. Process 1 is reversible adiabatic compression (3-4). Process 2 consists of reversible constant temperature heat addition (4-1). Process 3 consists of reversible adiabatic expansion (1-2).

Lastly the process 4 consists of reversible constant temperature heat rejection (2-3). The thermal efficiency of the Carnot cycle can be determined. One must note that for reversible case the magnitude of entropy change during heat addition and heat rejection are equal so that $T_H = T_1$ (or T_4) and $T_L = T_2$ (or T_3) since the heat transfer between the heat source and the working fluid occurs at no temperature difference. The Carnot cycle thermal efficiency is given by

$$\eta_{th} = (Q_A - lQ_Rl)/QA = \Delta W_{net}/Q_A = T_H(S_2 - S_3) - T_L (S_2 - S_3)/T_L(S_2 - S_3) = (T_1 - T_2)/T_1 = 1 - (T_2/T1)$$

The above relationship shows that the cycle efficiency is a function of temperatures of the heat source and heat sink and independent of the working fluid. Because this cycle is reversible it produces



Source: IEA

Figure 2: World primary energy into power generation.

maximum work possible of all cycles operating between the two temperatures of T_H and T_L. Furthermore the real cycle will have higher efficiency at higher maximum temperature at which heat is received and also at lower minimum temperature at which the heat is rejected. The A reversible cycle operating between two given temperatures has the highest possible thermal efficiency of all cycles operating between these two temperatures. Carnot cycle is reversible and therefore has the highest possible thermal efficiency between any two given temperatures.

3 Energy and Power Generation

The amount of energy used as well as the distribution of different kinds of energy used to produce power in the world is given in Figure 2. Coal oil and gas remain as the major sources worldwide. Renewable energy account for about 11.5% of the world primary energy and presently provides only about 2.1% of the power generation. Since the amounts of fossil energy available are limited we must make all the efforts to utilize the available energy at highest efficiency possible. Most simple cycle power plants have efficiency of the order of about 30-35%. This is because all practical cycles are not reversible and therefore have some efficiency (or entropy production) associated with them. As an example all turbines and pumps are never isentropic so that we must seek novel means to minimize the isentropic losses. Therefore, a design engineer always has a goal to maximize the efficiencies (or minimize the isentropic losses) by making some modifications to the cycles. A schematic diagram of the various losses associated with a power plant is shown in Figure 3. A number of methods have been used to minimize such losses. In no case has the irreversibility and other losses present in power plant been completely eliminated.

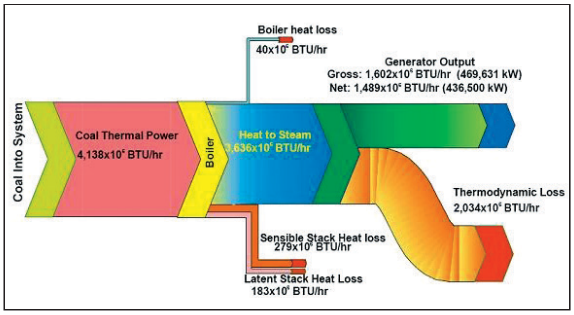


Figure 3: Major thermal energy power usage per unit time from a PC coal fired unit with no carbon capture.

3.1 *The steam cycle*

In the steam cycle, called Rankine cycle, steam at high temperature and high pressure produced from a boiler is expanded in a steam turbine. The work output is used to drive an electrical generator. The low pressure steam rejects heat in a condenser (heat sink) and the condensate (water) is pumped back to the boiler since the water treatment for use in a boiler must be free of unwanted dissolved and other materials that can adversely build up scaling on the inside surfaces of the boiler and boiler tubes. The thermal energy gained by water, to cool the condensate, is dissipated by the use of cooling towers. Thus, the coolant and condensate are kept separate to maintain the desired high quality water in the steam cycle. Steam cycle can use gas, oil, coal, biomass or their mixtures. The addition of small amounts of biomass (about 5 to 10%) to coal as fuel is particularly attractive because it does not require much hardware changes with significant benefits on reduction in fuel costs.

The most traditional approach to burn coal for steam power generation has been via pulverized coal combustion. In this approach the burners utilize very small size coal particles that are mixed with some air and injected into the combustion chamber for ignition and complete combustion within the combustion chamber. However, the fly ash leaving the combustion chamber at high temperatures and entering the convective section of the boiler must be cooled down to temperatures below its softening temperature in order to avoid fouling of the heat exchange surfaces. It is therefore important to consider important design considerations associated with coal combustion (that includes the process of coal devolitilization, ignition, and combustion and char burnout). Furthermore, the pollutant formation and destruction in the flames is critical as it determines the fate of pollutants emitted from the combustor/power system.

In the near term several options exist for the clean and efficient power generation using advanced Rankine cycle plants, such as, pulverized coal combustion with supercritical boiler with steam at 245 bar pressure and 565°C temperature, pulverized combustion in ultra supercritical boiler with steam at 300 bar and 600°C, ultra supercritical boiler with steam at 375 bars at 700°C temperature, and circulating fluidized bed combustion. The integrated combined cycle plants have higher efficiency than the simple Rankine cycle. The options here include: natural gas combined cycle (NGCC), pressurized fluidized bed combustion (PFBC) with topping combustion cycle, integrated gasification combined cycle (IGCC), and hybrid gasification/fuel cell/gas turbine/steam cycle (DoE vision 21 program).

3.2 *Pulverized-coal firing system*

Pulverized coal combustion in Rankine steam cycle mode has been the frequently used mode of burning coal in power plants since the 1920s worldwide with characteristic subcritical steam parameters of 163 bars and 538°C. The lower heating value (LHV) efficiency can be obtained as high as 40%. The pulverized coal combustion in supercritical boiler has been in operation since the 1930s with plant efficiency as high as 45% as illustrated by Schilling [2]. The first two are waste gas heat loss from the boiler that can be as much as 6 to 8% and represents largest heat losses from a boiler. The exit gas temperature from the boiler can be reduced from the dew point design considerations of the flue gases. The role of subcritical, ultra-critical and supercritical has significant effect on efficiency and percentage of CO_2 emission reduction. The plant efficiency increases by about one percentage point for every 20°C increase in superheat steam temperature. Figure 4 shows the net plant efficiency gains and carbon dioxide emission reduction obtained from going from subcritical steam plant to ultra-supercritical pulverized coal plant [3]. It is anticipated that with the new construction of ultra-supercritical plant in the next decade will provide efficiency of about 50% for coal-fired plant (LHV) which can also provide reduction of about 25% in carbon dioxide emission as well as significant reduction of other pollutants.

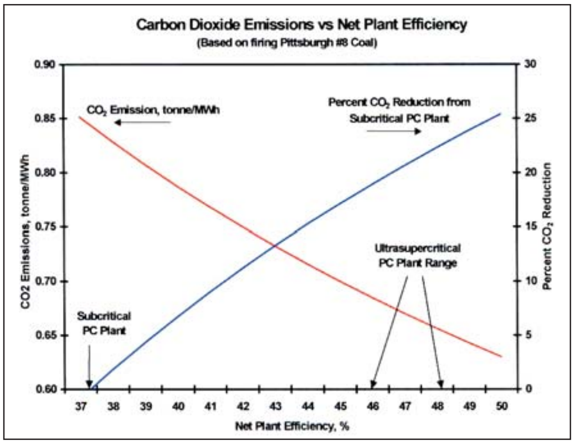


Figure 4: Net plant efficiency vs. carbon dioxide emission [3].

Relationship exists between the excess air of combustion and low limit of exit gas temperature using sulfur containing fuel. Excess air favors the oxidation of SO_2 to w, which is then converted to H_2SO_4 (sulfuric acid) in the combustion products. Sulfuric acid vapors increases the due point of the flue gases so that the permissible minimum exit temperature of the flue gases decreases (i.e., high exhaust gas temperatures). Only about 1 ppm of SO_2 in the gas stream raises the due point of the flue gases by about 62°C. This effect is not liner if the concentration of SO_2 increases to higher values. At stack gas exit temperature of 130°C, the plant efficiency increases by about 0.3% for every 10°C decrease in boiler exit temperature.

The pulverized coal system consists of coal pulverizer, fuel delivery and burning equipment to produce steam. A pulverized coal burner receives dried pulverized coal in suspension in the primary air and mixes with the main combustion air from the steam generator air preheater. The surface to volume ratio pulverized coal requirements vary from the coal type (the higher the fixed carbon the finer the coal). For example, pulverized coal with 80% passing through a 200-mesh screen and 99.5% passing through

50-mesh screen have a surface area of approximately 1500 cm^2/g with more than 97% of the surface area passing the 200-mesh screen.

The Rankine cycle efficiency is directly proportional to the pressure and temperature of the steam with which heat is added to the cycle and inversely proportional to the condenser pressure and thus the temperature of the cooling medium. The common design pressure is 2 inches of Hg absolute (about 67 mbar) in the USA while it is 1 inch of Hg absolute in Europe. This reduced pressure operation can provide net efficiency gains of about 2% in the power plant.

3.3 *Cyclone furnaces*

Cyclone furnace firing, developed in the 1940s represent the most significant step in coal firing since the introduction of pulverized coal firing in the 1920s. It is widely used to burn low grade coals with high as content (6 to 25%), high volatile matter (above 15%) and wide range of moisture content with pre-drying. One limitation is that the ash should not contain high sulfur content or high ratio of (Fe_2O_3/Cao + MgO). Such a coal has the tendency to form high ash fusion temperature materials in the slag, such as iron and iron sulfide in the slag, which provides detrimental effect on the use of cyclone furnaces.

The cyclone is essentially a water cooled horizontal cylinder that is located outside the main boiler furnace. Pulverized coal is fed into the cyclone to provide very high rates of heat release. The combustion is completed prior to allowing the hot gases enter the main boiler furnace. The swirling motion of the coal particles and air results in high volumetric heat release rates of 4700 to 8300 kW/m^2 (or approx. 450,000 to 800,000 Btu /$h.ft^3$) and high combustion temperatures, in excess of 1650°C. At such high temperatures the ash melts and flows along the walls of the cyclone and eventually drains through the slag tap opening at the bottom of the main boiler furnace. The slag is then solidified, crushed and removed to remote location for its further use in road bed and construction materials. The slag layer formed in the cyclone chamber acts as an insulator to minimize the heat losses through the walls of the cyclone thus contributing to enhance the efficiency of the system. The combustion of fuel occurs in the cyclone chamber. The boiler furnace has the main purpose of heating the water in the water tubes in the furnace boiler and produce steam. The high temperature in the cyclone produces high NO_x in the combustion products.

3.4 *Fluidized bed combustion*

In a fluidized bed combustion occurs at lower temperatures as compared to cyclone and PC boilers. The fluidized bed contains solid particles (sand) and fuel particles (coal) that are in intimate contact with a fluid passing through at a velocity sufficiently high to cause the particles to become freely supported by the fluid. In contrast the fixed bed has too low of a velocity to cause fluidization. The minimum fluid velocity necessary for fluidization can be calculated by equating the drag force on a particle due to the fluid motion to the weight of the particle. The fluidized bed provides intimate contact between the fuel and air and the combustion of coal particles occur in a hot bed of sorbent particles that are in the fluidized state. Enhanced heat transfer from the bed to the heat exchanger tubes that are embedded in the fluidized bed occurs in the fluidized combustor. Another advantage of the fluidized bed combustion is the removal of sulfur during the combustion process. Circulating fluidized bed (CFB) is the most common fluidized bed design today. In this design high gas velocities (about 4-10 m/s) entrain large portion of the solids which are then separated out from the flue gases and recirculated to the lower part of the furnace to achieve good carbon conversion efficiency and SO_2 sorbent utilization. A cyclone is used for the separation of particles and hot gases at the furnace exit.

Removal of sulfur dioxide during the combustion process is achieved with the use of limestone added to fluidized bed along with the crushed coal. The limestone is converted to free lime which reacts with SO_2 to form calcium sulfate. Under steady state conditions the fluidized bed consists of unburned fuel, limestone, free lime, calcium sulfate, ash and sand bed material. The temperatures in the bed are fairly uniform (850- 900°C) due to very good mixing and the residence times are very long so that carbon conversion efficiency is very high. The above combustion temperature range in the fluidized bed is optimum for in-situ capture of SO_2 by the available free lime in the bed. In addition the bed temperature is low for thermal NO_x formation. Therefore fluidized bed is also good from the point of view of NO_x emission. However, low temperature combustion in CFB (circulating fluidized bed) results in higher levels of N_2O emission (in the range of 40 to 70 ppm) since it survives at temperatures below 1095°C. N_2O is a green house gas with global warming potential of 296 times higher than CO_2 so that the characteristic N_2O emission from CFB corresponds to about 15% increase in CO_2 emisisons.

4 Efficiency Improvements in Power Plants

4.1 *Combined cycle power plants*

Fossil fuels constitute 85% of the total energy consumption. It is anticipated that this consumption will increase in the next 25 years. It is well known that the supplies and reserves of fossil fuels are limited, lasting to about 50 to 300 years depending on the fuel type, use, recovery rate and exploration. The use of fossil fuels suggests good evidence of increase in CO_2 emissions, global temperature and long term climate change. High efficiency systems as well as increased utilization of carbon neutral renewable energy (also nuclear fuels) offer the benefits of controlling the rate of CO_2 increase and global temperature rise. Current market share of renewable energy consumption is about 11.5% while electricity production it is only about 2.1%. Therefore, efforts must be made to enhance power plant efficiency using fossil and renewable fuels.

Combined cycle plants that incorporates gas turbine and steam cycle plants offer good advantages of enhancing the plant efficiency. This is because the temperature range of the Brayton (gas turbine cycle) and Rankine (steam cycle) are in successive ranges for the two cycles so that the waste energy from the gas turbine Brayton cycle (operational range 900- 1600K) can be used for operating the steam Rankine cycle (operational range 288 - 850K). Therefore, combined GT and stream cycle can provide greater thermodynamic cycle efficiency as compared to single cycle alone, see Figure 5 [1]. In a characteristic gas turbine cycle the thermodynamic efficiency from gas turbine can be about 38% and the rest of the energy (about 61.5%) is lost in the exhaust due to high temperature of the exhaust gases. The radiation losses account for only about 0.5%. However, if exhaust gases are used for operating steam turbine cycle, the efficiency of this cycle can be about 21% of the input fuel energy. The condenser losses in the steam turbine cycle account for about 30%, while stack and radiation losses account for 10% and 0.5%, respectively. Therefore, the net efficiency of the combined cycle plant is enhanced to near 59%. This net gain in efficiency has significant effect on energy use CO_2 and other pollutant's emission, and global temperature rise.

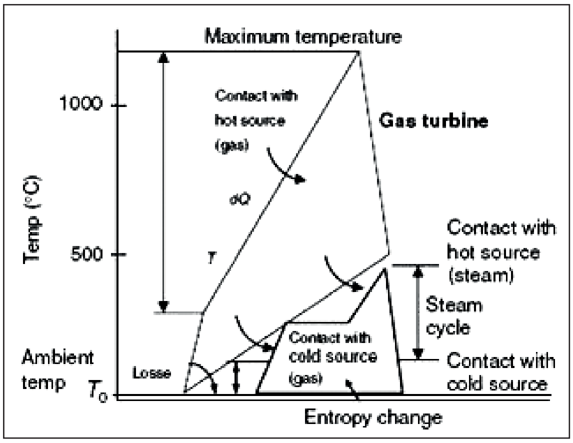


Figure 5: Temperature-entropy (T-S) diagram of combined cycle having Brayton cycle gas turbine and Rankine steam turbine cycle [1].

High carbon to hydrogen ratio of natural gas makes natural gas combined cycle power plants to be environmentally benign, this allowing them to be located in areas of high population density. These plants are primarily used as distributed power generation or heat and co-generation plants. However, due to high price of natural gas (as compared to coal on the basis of unit energy content) use for central power production is not economical. The use of coal is favorable due to its abundant supply in coal rich countries (e.g., the USA) and availability of clean coal technologies for efficient and clean power production. It is therefore favorable to use coal based technologies to produce power as coal is much cheaper than natural gas or oil. It is expected that this cost issue of high natural gas price as compared to coal will not change in the future also.

Pongprasert W. and Kerdsuwan [58] used a computer program that simulated the flow and control behavior of a characteristic Brayton cycle. This program allowed one to determine the characteristic operation of a Brayton cycle power plant without physically building a plant. The results obtained provided a fairly good agreement with those observed in real practice. Several other computer program exits in the literature that can simulate not only a Brayton cycle but also combined cycle, life cycle costs and impact of fuel property on system performance. These tools are good educational tools for providing enriched experiences to students, engineers and young professionals prior to actually operating a real power plant.

4.2 *Hybrid integrated power plants*

Combined cycle power plants use more than one unit to maximize overall efficiency by operating each unit within its own best designed parameter. In the case of combined cycle the wasted energy from the Braton cycle can be effectively used in the bottoming Rankine cycle. Many other examples exit on the use of integrated system, such as waste heat from the power plant for district heating, superheat and reheat cycles, hybrid power, energy conversion and propulsion units integrated through a storage unit. In the transportation sector, some specific examples of such hybrid systems include internal combustion engine/electric motor automobiles, fuel cell/batteries/internal combustion engines. Integration of conversion and storage units has been shown to be very promising in providing the mismatch between demand load and available energy source when using in intermittent sources. Advanced concept plants that use multiple energy sources, such as, fossil fuel and solar thermal energy, overcome the intermittency and maximize overall thermal efficiency. Combined power and heat units has been used in minimizing waste heat in decentralized power thus increasing overall efficiency of the plant. Integration can be in several forms that satisfy the specific criteria. We expect integrated systems will continue to evolve and grow further. This is true of larger electricity plants, with characteristic life time of about 50 years, so that they can reach efficiency of over 60% and capture all the CO_2 released from the plant for its sequestration or further use. Power plants and refineries can be integrated optimally to exploit the synergy between the processes of simultaneous electricity production and fuels transportation. Hybrid power trains that integrate high temperature fuel cells and thermoelectric devices with the internal combustion engine and battery will result in higher fuel mileage. Efficient and economical expansion in the use of renewable resources (since fossil fuels are limited) including biomass, wind, solar will greatly benefit from integration with fossil fuel systems. The effort to achieve maximum conversion efficiency through integration will not be successful unless it is followed by a gradual transition strategy that fosters economic and social issues. The examples of combined cycle power plants and hybrid power trains are good records of integrated energy systems as they are now commonly used and widely accepted.

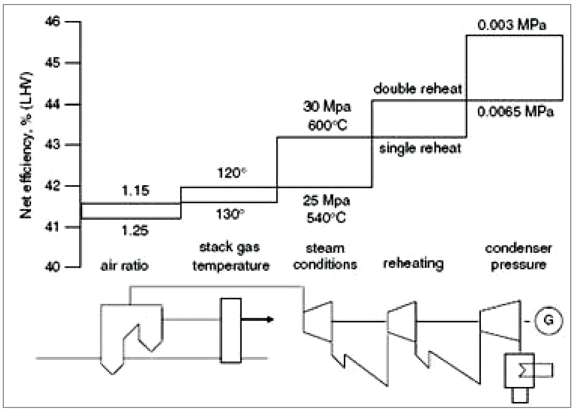


Figure 6: Increase in plant efficiency using various techniques.

4.3 *Other methods to increase efficiency*

The area under the P-V diagram curve provides the net power output from the plant. Therefore, operation at higher pressures and heat rejection at lower temperature provides increase in net power output. In Rankine cycle this has been used much in the industry. Many of the European power plants operate at supercritical steam temperatures while the North American plants are typically operated at lower steam temperatures. The increase in power plant efficiency associated with higher pressures and temperatures as well as reducing the discharge at lower pressures and temperatures results in higher efficiency. This is illustrated in Figure 6. Plant operation at higher temperatures and low back pressure can increase the plant efficiency significantly.

4.4 *Waste heat recovery for improving efficiency*

Plant efficiency increases with decrease in heat losses from the stack, operation at higher temperature and pressures, combined heat and power systems, use of integrated energy conversion systems.

In the combustion zone not all the heat is used to produce power. In practical power plants much of the heat is lost via the stack or tail end of the boiler or power plant, see Figure 7. By utilizing much of this waste heat significant gains in the thermal efficiency can be obtained. Characteristic efficiency of a power plant is only about 30%. However, by utilizing the waste heat significant increase in plant efficiency can be achieved. The extent of waste heat from a plant varies with the type of plant. This is because for each application there is certain temperature range of interest, see Figure 8.

5 High Temperature Air Combustion Technology (HiTAC)

Recent advances on High Temperature Air Combustion (HiTAC), also called colorless distributed combustion or flameless oxidation, have demonstrated significant energy savings, higher and uniform thermal field, lower pollution including noise, and smaller size of the equipment for a range of furnace applications. In HiTAC combined heat and gas recirculation are used to provide high temperature and low oxygen concentration so as to enlarge and control the flame thermal behavior. This technology has shown promise for much wider applications in various process and power industries, energy conversion and waste to clean fuel conversion. For each application the flow, thermal, and chemical behavior of HiTAC flames must be carefully tailored to satisfy the specific needs. Sample results are given from a few diffusion flames using high temperature combustion air. A specially designed regenerative combustion test furnace facility, built by Nippon Furnace Kogyo, Japan, was used to preheat the combustion air to very high temperatures. The flames with highly preheated combustion air were significantly more stable and homogeneous (both temporally and spatially) as compared to the flames with room-temperature or moderate temperature combustion air. The global flame features showed the flame color to change from yellow to blue to bluish-green to green to colorless or flameless distributed in the entire combustion zone over the range of conditions examined. In some cases hybrid color flame was also observed. The flameless or colorless oxidation of the fuel was observed only under certain conditions. Very low levels of NO_x along with negligible levels of CO and HC have been obtained using HiTAC. The thermal and chemical behavior of HiTAC flame depends on air preheats temperature, oxygen concentration of air, fuel chemical property and fuel-air mixture preparation. Waste heat from a furnace in high temperature air combustion technology is retrieved and introduced back into the furnace using a regenerator. These features help save energy, which subsequently also reduce the emission of CO_2 (greenhouse gas) to the environment. Flames

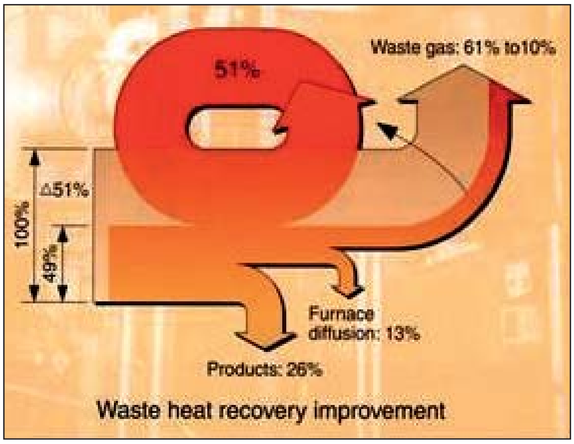


Figure 7: Waste heat from furnaces and potential improvement methodology.

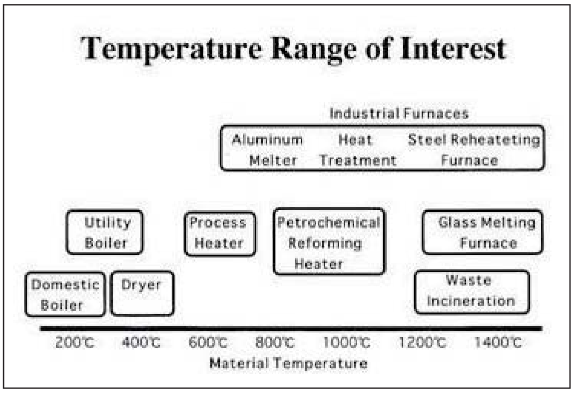


Figure 8: Temperature range of interest for various applications.

with high temperature air provide significantly higher and uniform heat flux than normal air, reduce noise, reduce the equipment size or increase material throughput for same size of the equipment. The high temperature air combustion technology have shown practical demonstration of significant energy savings (up to about 60%), downsizing of the equipment (about 25%), pollution reduction (about 50%), and low noise (about 7dB) in practical systems. Fuel energy savings directly translates to reduction of CO_2 and other greenhouse gases to environment. HiTAC has been used to demonstrate fuel reforming at high efficiency and also clean conversion of wastes to hydrogen-rich syngas and also liquid fuels.

5.1 *Background on HiTAC*

High temperature air combustion (also called colorless distributed combustion, flameless oxidation) of fuels is new and innovative method for the conversion of chemical energy to thermal energy from hydrocarbon fuels. The concept of excess enthalpy combustion was originated almost three decades ago for the combustion of low heating value fuels[4]. In excess enthalpy combustion the thermal energy released is fed back to the fresh reactants so that the temperatures obtained with excess enthalpy combustion are much higher than its counterpart with normal temperature air. However, colorless oxidation of fuels is obtained by using the design and fundamental principles of High Temperature Air Combustion (HiTAC) technology in which high temperature combustion air at low oxygen concentration (obtained by heat and gas recirculation) is mixed with the fuel prior to the combustion of fuel. High temperature air is obtained by preheating the air with the exhaust gases from the furnace or reactor. The peak temperature in the flame zone is much reduced with the use of diluted low oxygen concentration combustion air even though the air is preheated to high temperatures. This low oxygen concentration (or diluted) air is obtained by mixing portion of the exhaust gases by recirculating part of the combustion products into the incoming hot combustion air. The combustion air is preheated to temperatures in excess of 1000°C, depending on the application, using honeycomb type or ceramic ball type heat exchangers. Thus the HiTAC uses fresh air for combustion but this air is prepared such that the temperature and chemical composition is appropriate for the specific application to provide colorless distributed combustion. Honeycomb type heat exchangers are more effective than the ceramic ball type heat exchangers[5]. Most of the previous research activities have been focused on gaseous fuels, such as, methane, propane, liquefied petroleum gas (LPG) and process gases [5-37]. The HiTAC technology has also been demonstrated to provide significant benefits with other gas, liquid, solid and waste fuels[7,38] for applications to various kinds of furnaces, processes, and industrial and power systems.

Combustion researches are always concerned with meeting various industrial, societal, national and global needs. An example of this is excess enthalpy concept that was used for the combustion of low heating value fuels without using any auxiliary fuel. Global environmental problems, including acid rain, particulate, ozone layer destruction, and global warming from greenhouse gases, such as CO_2 and methane, are now recognized to cycle between atmosphere and the earth. Simultaneous requirements of both environment protection and energy conservation require rapid development of combustion science and technology for various applications. The science and technology of combustion has made significant progress during the past century, in particular after the World War II. For the furnaces area, HiTAC technology has shown revolutionary demonstration for energy conservation, reduction of pollution generation including NO_x and CO_2, far uniform thermal field and higher heat flux than previously possible, to give superior quality product [7,13,33]. Higher heat flux is from increased radiative heat transfer. This increase is from higher and superior uniform temperatures in the entire combustion chamber.

Recent progress on HiTAC is first reviewed here followed by hydrocarbon fuel reforming to hydrogen and more recent application of HiTAC for the gasification of coal, wastes and low grade fuels to produce hydrogen-rich syngas. Data are obtained from laboratory scale investigations as well as pilot plant studies in Japan [33]. Uniform thermal field in HiTAC furnace has also been used for fuel reforming of hydrocarbon fuels to hydrogen [37]. The gasification studies provide innovative technology to convert wastes to hydrogen-rich syngas [38].

Fossil fuels, such as, coal, oil and gas, have been used by the society for millions of years. These fuel sources have never been considered exhaustible until recently. Rapid industrialization and growth of human society has resulted in rapid utilization of natural resources on the earth. This then leads to the reality that in the very near future the fossil fuels, which encompassed our main energy consumption cycle, will run out. Although the nuclear and solar energy may provide more promise for future, fossil fuel cannot be quickly replaced for all applications, at least in the near future because of their unique advantages including mature utilization technologies, non-radioactivity, safety, high conversion efficiency and cost effectiveness. However, when one considers the negative impact of fossil fuels, besides the limited reserves, concerns over environmental issues is quite serious.

The HiTAC technology is one of the most promising combustion techniques that provide solution for energy savings and pollution formation and emission. HiTAC technology is particularly attractive for processes that require uniform temperature, and higher and uniform heat flux distribution in the combustion zone, and low noise. Controlled flame behavior results in uniform thermal field, significantly lower emissions including combustion noise, and smaller chamber size for processing the same material or increased material throughput for the same furnace size. However, in order to explore further the full potential of high temperature air combustion technology, one must seek greater understanding on the detailed structure of highly preheated air flames so that the results can be translated to wide applications.

5.2 *Benefits of high temperature air combustion technology*

5.2.1. Energy saving

High-temperature air combustion technology uses regenerative heat exchangers to extract thermal energy from the waste gases in the combustion products. Ceramic honeycomb or balls have been shown to provide good energy storage heat media heat exchangers. Honeycomb type heat exchanger is more effective than ceramic ball type as this provides larger surface area, low-pressure drop and high efficiency. Exhaust gases from industrial furnaces and processes represent one of the major heat losses from the system. The regenerative media used in the HiTAC devices recovers large amounts of thermal energy from the exhaust gases which can then be transported back to the combustion zone. The amount of energy recovered translates directly into fuel saving. In the ‘High Performance Industrial Furnace Development’ project [2,30], the objective was to demonstrate significant energy savings (about 30%) using regenerative media, reduce physical size of the equipment by about 25%, and pollutants emission reduction (about 50%). Indeed the high temperature air combustion technology has demonstrated average energy savings of about 30% from industrial furnaces. This goal was successfully demonstrated using 167 field demonstration tests [7,33] with energy savings of 150,000 kiloliters of fuel. Now this technology is used in many countries worldwide.

5.2.2. CO_2 reduction

The role of CO_2 in global warming phenomena is now widely recognized. The demands for reducing CO_2 emission are higher than ever before. All fossil fuels contain carbon, which generate CO_2 as a byproduct during the combustion of carbon so that any efforts to reduce energy consumption will directly translate to reduction of CO_2 emission. Good correlation between fuel consumption and CO_2 production suggests that CO_2 reduction should be nearly the same as energy saving [33].

5.2.3. NO_x reduction

Emission of NO_x is now known to be responsible for the destruction of ozone layer in the upper atmosphere. In addition N_2O emission is of concern from combustion systems (for example in low temperature combustion devices, such as fluidized bed, that produce several tens of ppm of N_2O. This gas has 296 times more greenhouse gas potential than CO_2. NO_x (primarily NO and NO_2) involves the complicated reaction mechanisms, which result in accelerating the ozone depletion in the oxygen cycle on earth. Therefore, combustion engineers have focused their attention to develop various strategies to reduce NO_x emission and improve the combustion process. HiTAC is one of the most advanced techniques because of low levels of NO_x formation and emission, significant energy savings and uniform thermal properties in the entire combustion space [7,22,24,33].

5.2.4. Equipment size reduction

Higher and far uniform thermal field and heat flux distribution is obtained with HiTAC technology as compared to any other known method for combustion using normal temperature air [16,17,33], air preheated to some moderate temperatures using recuperators or with the use of air preheaters. The ignition delay time is different as compared to that obtained with room temperature air for combustion [8,11]. This means that many industrial combustion equipment has potential for reduced size, better product quality from the process and material's conservation with high temperature combustion air technology [18,24,33].

5.2.5. Noise reduction

Recent studies on HiTAC have shown significant reduction (over 7 dB) in combustion noise from HiTAC flames. This is attributed to smaller volumetric expansion with the HiTAC flames caused by distributed combustion features. Results on noise reduction under colorless distributed combustion conditions are given in refs. [33-36].

5.2.6. Uniform thermal field

The HiTAC combustion technology has shown temperature distribution uniformity in the entire combustion to be better than 30K. This has never been possible before so that one can classify HiTAC to be an isothermal reactor. Simultaneous realization of the above benefits was combustion engineers dream and considered impossible before. The unique flame features associated with HiTAC assists in utilizing this technology for wider range of applications than initially envisioned [7,13,33].

5.3 *Basic principle of HiTAC technology*

5.3.1 Thermodynamic consideration of combustion process

Flame temperature is one of the important factor for considering combustion efficiency and energy conversion efficiency. Weinberg [4] provided initial concept of excess enthalpy combustion. In his study, limitations on combustion temperature were discussed, including both positive and negative factors associated with combustion temperatures in a certain range. Heat circulation from the exhaust gases, using high-efficiency heat exchanger, was adopted in order to increase the combustion temperature thus allowing the combustion of low heating value fuels that could otherwise not be combusted without using auxiliary fuel. However, combustion engineers have to pay attention to the upper limit of combustion temperature because of materials constraints used in the equipment and/or pollution formation at higher temperatures, in particular NO_x. Various possibilities on enthalpy intensification have been described [5]. From the economic point of view, it is of course better to use thermal energy generated by combustion process itself to heat-up the oxidant or fuel, which is often of low thermal energy, than via the use of electrical or mechanical energy.

The amount of combustion-generated energy circulated into the combustion process is given as [4]:

$$\int_{T_0}^{T_t} C_p dT = Q_c + Q_a = H_t - H_0$$

where, T_f is the final temperature, T_0 is the initial temperature, Q_c is the heat release by chemical energy conversion, Q_a is the energy added, H_t and H_0 are the enthalpy at two states. The circulation part of thermal energy from combustion-generated products will increase the combustion temperature so that enthalpy of the reaction zone will be above the conventional combustion level. This has resulted in the use of term called "Excess Enthalpy Combustion".

Increase in thermodynamic efficiency must be coupled with other desirable characteristics, such as low NO_x formation, reliability of the equipment and refractory material, and spatial uniformity of temperature. Nonetheless the heat circulation and excess enthalpy methods provide new light on next generation of advanced energy conversion technology and combustion chamber design. This method provides new ideas to control temperature in the combustion zone. The method is independent of the fuel composition, and can simultaneously satisfy the demands of high combustion intensity and reduced pollutant formation from fuels, including low-grade fuels.

5.3.2 Basics of excess enthalpy combustion design

Excess enthalpy combustion can be realized by internal or external circulation or their suitable combination. Most designs for internal heat circulation use bluff body, porous media or swirl to the flow. Most of these are aimed at flame stabilization [19] and are very effective. Internal heat circulation relies on heat convection and species circulation so that pool of hot and active radicals in reaction zone can be maintained, which also assists in flame stabilization.

The external circulation methods use heat exchanger to transfer the thermal energy via conduction between combustion products and solid media so that heat can be exchanged to the cool reactants. Most of the enthalpy contained in hot combustion products can be recirculated back to the combustion process. This allows one to utilize much of the waste energy for flame stabilization.

5.3.3 Excess enthalpy combustion and high temperature air combustion (HiTAC)

Thermodynamic considerations suggest that preheating the oxidant to very high temperatures (not fuel due to possible fuel decomposition and safety) increases the cycle thermal efficiency. Air preheats add enthalpy to the combustion zone. From the point of pollutant formation, especially NO_x, high temperature of combustion has been recognized to be one of the most important parameter for high levels of NO_x emission. This then requires method to control the emission of NO_x. One method of maintaining the same temperature in the combustion zone is to dilute the incoming combustion air with hot combustion products to cause mild combustion condition. Partial recirculation of hot products into the incoming combustion air dilutes the inlet concentration of oxygen in the air. This diluted air lowers the peak flame temperatures with negligible oxidation of N_2. Further examples of this are given in refs. [5,7,20,33].

The goal of HiTAC was to demonstrate significant pollution reduction from industrial furnaces (by about 25%), enhance efficiency and achieve fuel energy savings (by about 30%), reduce equipment size (by about 25%), and reduce noise (by about 7 dB) using honeycomb type regenerative burners that can be classified to operate using excess enthalpy principles.

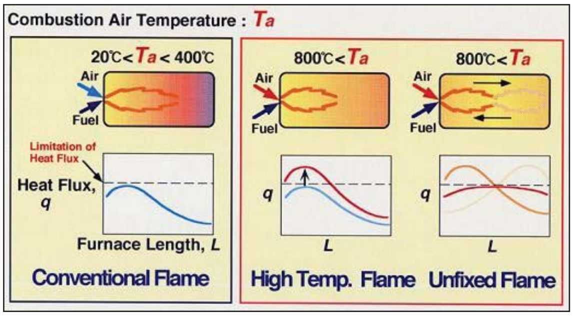


Figure 9: A Schematic diagram of flame and heat flux distribution in a furnace with low temperature combustion air, high temperature air, and high temperature and low oxygen concentration air (HiTAC) condition.

In the North American design, ceramic balls have been used in the regenerators to preheat the combustion air with hot gases exiting the furnace. The use of ceramic balls in a packed bed provided higher combustion air temperatures; however, the regenerator efficiency is not so high as compared to honeycomb type regenerator. Nonetheless the air preheat temperatures were much higher than those achieved previously with the use of recuperators. In the High Temperature Air Combustion (HiTAC) technology of NFK a honeycomb type regenerator is used. The honeycomb regenerator is much more compact than a bed packed with ceramic balls, because of high specific surface area, low thermal inertia and gives very low-pressure drop [5,18]. In the HiTAC technology low oxygen concentration air at high temperatures is used for combustion air. In conventional burners increasing the air preheat temperature increases NO_x emission levels. However, with high temperature combustion, the temperature increase in the furnace or reactor is small (only about 30 to 100°C above the incoming high temperature combustion air). The oxygen concentration in the combustion air is very low (only about 2 to 5% by volume, depending on the application). Under these conditions the thermal field in the combustion zone is very uniform [17,32,33]. The peak temperatures in the combustion zone are suppressed to result in very low NO_x emission levels. The heat flux from the flame with high temperature combustion air is also very high [16,17,33]. A schematic diagram of the flame and heat flux distribution with normal temperature air and high temperature combustion air (called HiTAC flame) is shown in Figure 9. The HiTAC flame results in very

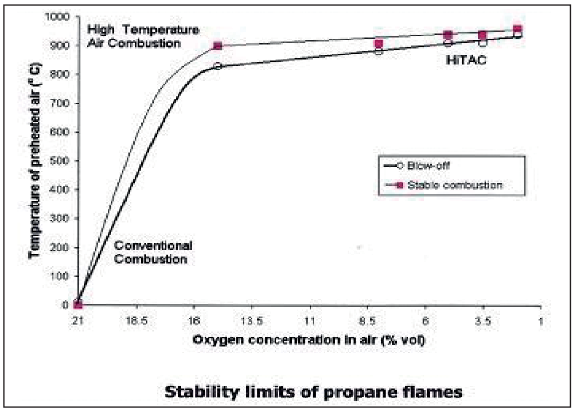


Figure 10: Stability limits of the propane flame as a function of air preheat temperature (heat recirculation) and oxygen concentration in air (flue gas recirculation).

uniform thermal field and high and uniform heat flux in the combustion zone.

5.4 *Flame characteristics with high temperature air*

5.4.1 Flame stability and characteristics

The flame characteristics of propane fuel and high temperature combustion air have been examined in the test furnace facility using several advanced diagnostics. The flame stability limits of propane fuel as a function of air-preheat temperature and oxygen concentration in air is shown in Figure 10. The flame is stable above the curve shown in the Figure. The flame stability limits increase significantly at high air preheats. Note that very wide flame stability limit occurs even with low oxygen concentration air. Under HiTAC conditions (high temperature and low oxygen concentration air) the flame stability limits are essentially infinite. The results also suggest that it is possible to use exhaust gases from a furnace as oxidant since these gases often contain several percent of oxygen.

The test regenerator facility utilized could provide high temperatures with any gas mixtures to about 1100°C. The size and color of these flames depend on air preheat temperature and oxygen concentration (or the amount of gas recirculation) in the combustion air and fuel property [7]. All flames showed very different flame structure as the air-preheat temperature was increased and the oxygen concentration in air was reduced from 21% to less than 5%. The flame volume was found to increase with increase in air preheat temperature and decrease in O_2 concentration in the combustion air. At any fixed temperature, the total flame volume decreased with increase in oxygen concentration from 2% to 21%. No yellow color flame was found at temperatures below 950°C and oxygen concentrations below 15%. The size of blue color region in the flame decreased with increase in oxygen concentration (up to about 15%) and temperature. The flames were of blue color for air preheats temperature between 900° to 950°C and O_2 concentrations between 5 to 15%. For very fuel-lean mixtures at high air preheat temperature (1100°C), the luminosity of the flame (and hence the heat flux) was found to be very high. Further discussions on flame features are given in refs. [4,7,33,34]. At high air preheat temperatures and low oxygen concentration of about 2 - 5% in air, the flame was found to be of green color. The green flame color, which is considered as environmentally benign, pronounced at higher air preheats and low oxygen concentration in the combustion air. This is due to high levels of C_2 species (swan band) produced from within the flames under these conditions. Low reaction temperatures cause increased production of swan band C_2 species in flames while normal flames cause blue color at high reaction temperatures. A dramatic increase in the flame volume was obtained with low oxygen concentration and high temperature combustion air. No flame color could be observed at very low O_2 concentration in air (about 2% or less). We describe this condition as colorless oxidation of fuel (also called Flameless oxidation of fuels). Sample photograph of the colorless combustion is shown in Figure 11.

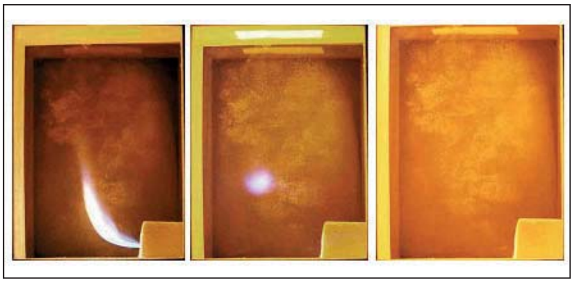


Figure 11: Methane flame photographs with combustion air temperature of 1000°C and oxygen concentrations (from left to right) of 21%, 8% and 2%, respectively. Note the colorless combustion in the extreme right side flame photograph.

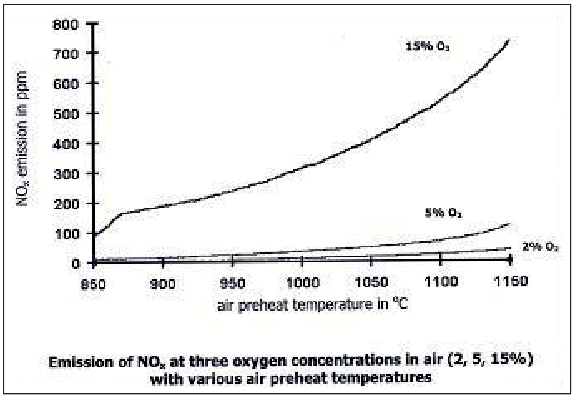


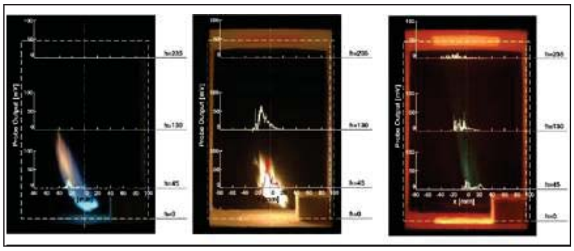
Figure 12: NO_x Emission as a function of air-preheat temperature and O_2 concentration in air using propane fuel.

5.4.2 NO_x emission

In order to determine whether high temperature combustion air would adversely affect pollution emission, measurements were made of various gaseous species. Figure 12 shows the NO_x emission levels for propane flame as a function of air preheats at 15, 8 and 2% O_2 concentration in air. The emission of NO_x increases with air preheats temperature under normal combustion conditions. This was also true for HiTAC conditions but the rate of increase was very small. Very low NO_x emission is observed under high temperature and low oxygen concentration combustion conditions. NO_x emission at air preheats temperature of 1150°C decreased from 2800 ppm at 21% O_2 to 40 ppm at 2% O_2.

5.5 *Diagnostics for colorless distributed combustion (Flameless oxidation) in HiTAC*

Flameless oxidation of fuels means no visible flame so that the diagnostics used must be carefully selected to observe the flame features. The radiation from the HiTAC flame is not luminous as it is primarily from water vapor (steam) and carbon dioxide. In addition the temperature rise in the HiTAC flame is small. Most of the required heat is provided from furnace wall as solid radiation. Several diagnostic techniques may be considered to monitor the fate of flames in furnaces. They include PLIF, optical measurement of chemiluminesence spectra, FTIR, GC/MS via gas sampling and ion concentration measurement. Some of these techniques are expensive and not easily adaptable to hostile industrial size furnace environments. Ion concentration measurement with electrostatic probe has the advantages of high sensitivity response, can withstand hostile environment, and low cost. Electrostatic probe utilizes conductive characteristics of the combustion reaction zone. During the combustion of hydrocarbon fuels, high level of ion concentration is formed by the chemical ionization reaction. A new practical diagnostic technique, based on the modified electrostatic probe, has been successfully developed and used to monitor ion concentration in the flame zone. The technique has been applied to monitor invisible-HiTAC-flame for improving heating performance in a test steam reformer furnace [35]. The diagnostics was first developed using a 1.3kW HiTAC furnace facility and then applied on a pilot plant fuel reformer facility.



a) b) c)

Figure 13: Direct flame photographs and flame ion concentration from ordinary, high temperature and HiTAC flames.

Figure 13 shows a comparison of the radial distribution of flame ion concentration at selected axial positions in the flame measured with the ionization probe (units in mV) from three different flames (ordinary flame, (left), high temp. air flame (middle), and HiTAC flame (right)) using the 1.3 kW furnace facility [36]. The results are shown on the global flame behavior superimposed on the ionization probe data with the probe traversed horizontally at 3 different heights of h = 45, 130, and 235 mm. The results for the normal air (25°C temperature, Figure 13a), high temperature air (21% 0_2, in excess of 1000°C air preheats, Figure 13b), and diluted and high temperature air with 3% 02 (HiTAC case, Figure 13c). For the case of ordinary flame with ambient temperature combustion air, shown in Figure 13a, although some level of output signal is obtained from the ionization probe at h = 45mm, no signal is obtained at h = 130mm.

The flame ion concentration is detected only in the areas where the flame is present, Figure 13. No signal is detected with the probe outside the flame areas where no visible flame is present [36]. The results clearly show high level of ion concentration signal obtained for the high temperature combustion air case. Relatively low level of ion concentration obtained for the HiTAC case, shown in Figure 13c, suggests that the technique is capable of providing information under flameless oxidation conditions so long as the chemical reactions continue to occur in the flame. The results showed that the measured ion concentration is proportional to the probe size. A larger size probe was developed at NFK for use in full-scale reformer furnace (hydrocarbon to hydrogen transformation reformer facility) with good success. The results obtained showed that the flame ionization probe is a good diagnostic tool for application under distributed colorless combustion conditions.

5.6 *Waste disposal*

The most common and often used method of waste disposal is landfill as it is easy and less costly to the disposer but poses long term issues on environmental and water pollution. In some countries (such as Japan) the landfill disposal of municipal solid wastes is not an option as it creates bacteria growth, create bad odors, attracts rats and other mammals so that nearby habitants gets much impacted. The greenhouse gases emitted from the slow degradation of wastes is also an issue. In recent times several utility companies have used these landfill sites to produce landfill gas that is used in a power plant to produce electricity. Although much of the landfill gas is collected but some is still released to the environment and the environmental and water pollution still remain an issue. The methane gas released is about 23 times more in greenhouse effect than CO_2. Therefore with the increased waste production worldwide, both with increased population, increased activity and standards of living one must use a strategy that is sustainable.

The other option for waste disposal is mass burning. In this method the waste is ignited in the open and the pollutants released to the environment. Some of the pollutants are carcinogenic and mutagenic from the open burning. This is a volume reduction method wherein the waste volume reduction is about 90% so that 100 cubic yard of waste reduced to 10 cubic yard of ash (inert material). The amounts of carbon, particulate emission and trace pollutants released from mass burning are significant so that this method is not sustainable. No energy is recovered from this method so that it is a volume reduction method for permanent disposal of the waste. The energy released is totally wasted. Note that wastes have heating (calorific) value and for dry waste it is ~6,968 Btu/lb (or 13.5 MJ/Kg). For comparison purposes the heating value of sub-bituminous coal is 11,729 Btu/lb (or 27.3 MJ/kg). The heating value decreases with moisture content in the waste so that for 50% moist waste the heating value is only about 3,380 Btu/lb (or 6.54 MJ/kg). In the USA the amounts of wastes produced are about 4.3 lbs/person/day, and UAE about 4.5 lbs/person/day. They are amongst the municipal waste produces in the world. However, in Japan the amounts of solid waste produced per capita per day is only about 2.2 lbs. The GDP of a country is directly correlated with the amounts of solid waste produced. The increased economic activity leads to more solid waste production. In the USA much of the waste is disposed-off using landfills and this practice is quite common in most parts of the world because of low cost associated with this method and that much land exists that is available for landfills. In addition to landfills the waste is also converted to electricity. In the USA 249 million tons of solid waste goes to trash while only about 29 million tons of waste goes to electricity production. It is interesting to note that renewable energy generated from landfills is 5 billion kWh while that from electricity from waste is 15 billion kWh. In other words one ton of waste produces about 120kWh of electricity from landfills but it is approximately 700 kWh from waste to electricity plants. This provides the rationale for using more waste to electricity plants than using the route of landfills to electricity.

5.6.1 Waste to energy

The most common method of solid waste to energy conversion is mass burning wherein the waste is uniformly distributed on a grate and the air is passed

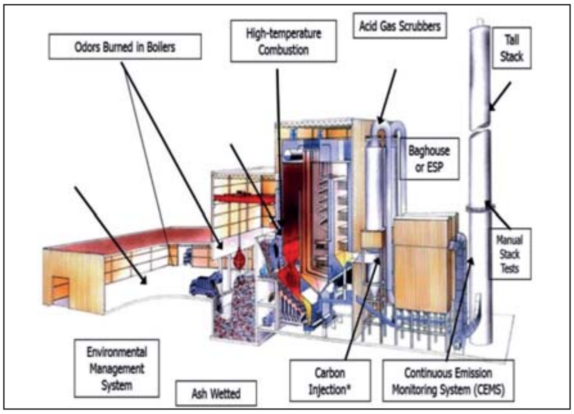


Figure 14: Typical waste to energy plant.

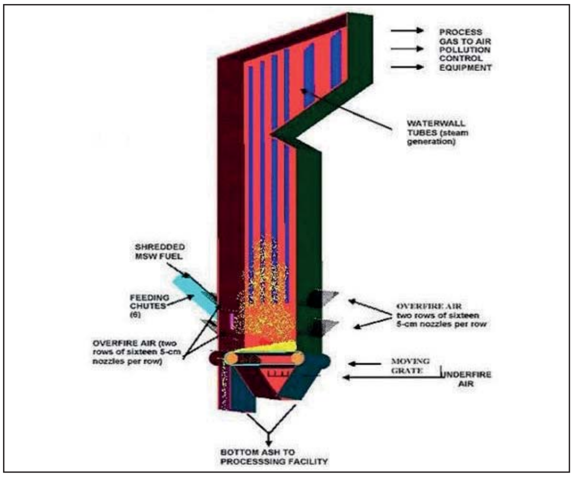


Figure 15: Advanced waste to energy technology with part of the combustion on the grade and part in the suspended region of the combustion chamber.

from below so as to provide good interaction between the waste material (hydrocarbons or biomass). The combustion occurs above the bed. The grade bed can be fixed or moving. If it is fixed then a reciprocating device is used so that the waste material is pushed down to provide additional mixing between waste material and air. In most cases the bed is sloped slightly downward so that the burning material gradually moves downward. The length of the bed is such that by the time burning waste material is towards the end in the combustion chamber it is all combusted. A typical waste to energy plant sketch is given in Figure 14.

The combustion chamber involves a grate type of bed over which the solid waste material is spread and combustion occurs above the bed. The waste is introduced into the combustion chamber via a hopper so that the initial zone is drying zone, followed by pyrolysis zone where the volatiles are evolved that rapidly mix with the surrounding air to produce heat. This is also a mass burn type of controlled burn incinerator with the heat produced utilized to produce steam which is then used to produce electricity. Steam is squeaky clean and can be used for local heating and cooling purposes. There are many plants that convert waste to squeaky clean steam. It is a very good means to manage the wastes. However, the mass burn incinerators produce many pollutants that are released to the environment. In order to reduce pollutants emission to the environment several other designs of waste incinerators have been developed that are more environmentally benign. These include pyrolysis and gasification. Pyrolysis is heating up of the material in the absence of air or oxygen while gasification is heating up of the material in the presence of some gasifying agent. Advanced design of the chamber involves combustion immediately above the bed and above the bed using pulverized materials of waste so the material is suspended in the combustion chamber as shown in Figure 15.

Gasification is heating-up of carbonaceous fuels with some gasifying agent to produce gases fuels. It does include the technologies partial oxidation or fuel rich combustion, and hydrogenation. In the partial oxidation process the oxidant (also called the gasifying agent) could be air or some mixture of gases. The characteristic gasifying agents used include air, oxygen, carbon dioxide, steam and ultra-high temperature (over 1000°C) steam. The heating value of the gases produced is low with air as gasifying agent while with ultra-high temperature steam it is medium to high. This definition excludes combustion, because the product flue gas has no residual heating value. High temperature steam provides hydrogen rich syngas. The gasifying agent is chosen according to the desired chemical composition of the syngas. In order to achieve high hydrogen yield, steam is chosen for gasifying agent. The final composition of the syngas is a function of the gasification temperature, steam to carbon ratio and pressure. Consequently, adjustment of these parameters should be taken into consideration to optimize thermal efficiency. During the process of gasification of solid carbon whether in the form of coal, coke, or char, the principle chemical reactions are those involving carbon, carbon monoxide, carbon dioxide, hydrogen, water (or steam), and methane using wide variety of solid wastes [38-43].

Combustion reactions:

$C + ½O_2 = CO, \Delta H = -111$ MJ/kmol
$CO + ½O_2 = CO_2, \Delta H = -283$ MJ/kmol
$H_2 + ½O_2 = H_2O, \Delta H = -242$ MJ/kmol

The Boudouard reaction:

$$C + CO_2 \Leftrightarrow 2CO, \Delta H = +172 \text{ MJ/Kmol} \quad (1)$$

The water gas reaction:

$$C + H_2O \Leftrightarrow CO + H_2, \Delta H = +131 \text{ MJ/Kmol} \quad (2)$$

The methanation reaction:

$$C + 2H_2 \Leftrightarrow CH_4, \Delta H = -75 \text{ MJ/kmol} \quad (3)$$

Reactions from (1), (2) and (3) are the most important reactions in the char-gasification step and both are endothermic reactions. These reactions are reduced to the following two homogeneous gas reactions.
Water-gas shift reaction:

$$CO + H_2O \Leftrightarrow CO_2 + H_2$$
$$\Delta H = -41 \text{ MJ/kmol} \quad (4)$$

The steam methane reforming reaction:

$$CH_4 + H_2O \Leftrightarrow CO_2 + 3H_2$$
$$\Delta H = +206 \text{ MJ/kmol} \quad (5)$$

A simplified reaction sequence for coal or biomass gasification is shown in Figure 16.

Solid fuels, such as, fossil fuels, biomass and municipal wastes consist of high percentage of volatile matter. These volatile matters differ in their chemical composition and chain length which affect their thermo-chemical behavior. The thermo-chemical properties affects the nature of hydrocarbon chain length present in the volatile phase and determine in part the evolutionary behavior of syngas chemical composition and flow rate during the gasification process. The change in syngas chemical composition of the syngas evolved has been determined using micro gas chromatography (GC) [41-43]. During experimentation, trace amounts of fixed flow rate of an inert gas (He) was added to the steam line. The inert gas was detected by the GC and assists in determining the instantaneous flow rate of important species in the syngas. Each component of the syngas showed a different behavior from the point of view of molar concentration and flow rate. The information on the evolutionary behavior of hydrogen flow rate, hydrogen concentration, hydrogen to carbon monoxide ratio, syngas heating value and other properties concerning thermal efficiency and effectiveness of the process is available [41-43]. The effect of steam flow rate on the evolutionary behavior of syngas chemical composition and flow rate of main species has also been investigated [42-43].

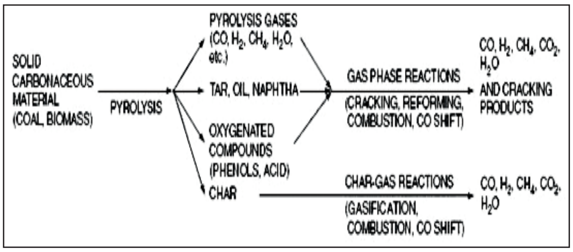


Figure 16: Temperature range of interest for various applications.

5.6.2 Effect of steam flow rate

Javier et al. [44] investigated the effect of steam to oxygen ratio in the gasifying agent on the syngas properties and concluded that LHV decreases with decrease in H_2O/O_2 ratio, because of in-situ combustion of some gas components with the addition of O_2 fed to the system. However when gasifying agent-to-biomass ratios (for a given H_2O/O_2 ratio) is increased, the LHV decreases by the same reason (more O_2 is fed) [44,45]. Consequently, the thermal efficiency decreases with increase in gasifying agent-to-biomass ratios [43].

The general trend of increase in the steam to sample ratio is to increase the yield of total syngas, H_2, and CO_2, while CO and CH_4 yields decreases [46-51]. The increase in H_2 and CO_2 yield and the decrease in CO yield are attributed to the acceleration of the forward reaction rate of the water gas shift reaction

($CO + H_2O \Leftrightarrow CO_2 + H_2$) [46,48-51]. On the other hand the increase in steam to sample ratio increases the methane reforming reaction to cause a reduction in the yield of methane [47]. Therefore, increase in steam to sample ratio results in a direct increase in the ratio of H_2/CO [47,49].

5.6.3 Air versus steam gasification

Steam gasification favors steam reforming reactions, while the air gasification promotes combustion reactions. H_2 and hydrocarbons yields with steam gasification are higher than those with air injection, whereas CO and CO_2 are lower, since the extent of combustion of char and volatiles is reduced by replacing air with steam. It is also expected that CH_4 and other hydrocarbons concentrations would be lower, since the equilibrium of water gas-shift reaction favors H_2 production. Steam reforming of tars ($Tar + H_2O \Leftrightarrow xH_2 + zCO$) and of hydrocarbons ($C_nH_m + nH_2O \Leftrightarrow (n + m/2)\ H_2 + nCO$) favors H_2 production, accompanied with a decrease in hydrocarbons content in the exit gas [52,53].

Ocampoa et al. [54] investigated experimentally the gasification of Colombian coal in a fluidized bed. Experimental results showed a maximum in the HHV curves versus air to coal ratio. The highest gas heating value of 3.3 MJ/m^3 was obtained using a steam/coal ratio of 0.71 and an air/coal ratio of 2.6.

5.6.4 Reactor temperature

Javier et al. [44] investigated the effect of different operational condition on the syngas chemical composition and properties. As a part of their investigation they examined the effect of reactor temperature on thermal efficiency of the process which increased with increase in reactor temperature. This is attributed to the endothermicity of the gasification process. The yields of H_2 and CO increases with increase in reaction temperature since the gasification reactions are endothermic. The data showed that the increase in gas yield with reaction temperature is partly achieved at the expense of tar and liquids [9,10]. The LHV increases a little with increase in reactor temperature due to increase in the yields of C_2H_2, H_2, and CO. The C_2H_m species are formed by the (steam) cracking of aromatic components of the tar [4].

5.6.5 Catalytic gasification

The low heating value (LHV, kJ/m^3) of the gas decreases somewhat when dolomite is used in the gasifier bed. This decrease can be due to the decrease in the amounts of light hydrocarbons in the flue gas. However, it is again verified how some dolomite in the bed has a positive effect; it increases the thermal efficiency from 86% to about 96% [8,11]. Jose et al. [55] investigated the effect of placing the dolomite in a secondary reactor downstream from the primary gasifier on properties of the syngas. The study provided no important differences between the two locations of the dolomite (i.e., inside the primary gasifier or downstream of the primary gasifier). This finding reveals that increase in the amount of H_2 in the flue gas is compensated with the decrease in amount of CO and also by the non-important variation in the amounts of CH_4 and C_2H_n in the flue gas. Therefore, there is no difference between locating the dolomite in the same gasifier bed or in a downstream reactor from the point of view of LHV of the gas.

5.6.6 Hydrogen production using chemical looping

Lin et al. [56] investigated the production of hydrogen using a combination of two chemical loops. The first is a water cycle. Water reacts with hydrocarbons to produce hydrogen and CO_2 and absorbs heat. The hydrogen then reacts with O_2 to produce power and forms H_2O again. The second chemical loop is the calcium oxide cycle. CaO first reacts with high-pressure H_2O to form $Ca(OH)_2$ and then absorbs CO_2 to form $CaCO_3$ and releases heat. The CaO is then regenerated from $CaCO_3$ for recycling ($CaO – CaCO_3 – CaO$) and releases CO_2. They achieved a cold-gas efficiency of 90% for product gas from coal.

5.6.7 Effect of H/C ratio in feed stock

Increasing H/C ratio in the biomass by increasing the moisture content in the sample increases the H_2 content in the raw syngas produced. The LHV (kJ/m^3) of the gas also increases as a result of increase in the H/C ratio in the biomass sample. More important is the effect of H/C on the tar amount present in the raw syngas. On increasing the H/C from 1.6 to 2.2, caused the tar content to decrease from 18 to 2.0 g/m^3 [45].

The decrease in tars and increase in H_2 and CO are due to the steam reforming effect of hydrocarbons and tar ($C_nH_x + mH_2O \Leftrightarrow nCO + (m + x/2)\ H_2$). By increasing the partial pressure of steam in the gasifier, favors the reaction ($C_nH_x + mH_2O \Leftrightarrow nCO + (m + x/2)H_2$) with important benefits of decreased tar and increased yield of H_2 and CO [4].

5.6.8 Gasification using supercritical water

Supercritical water mixes with most of the organic compounds so that rapid and homogeneous reactions of organic compounds are possible in supercritical water. Yukihiko et al. [57] investigated the energy efficiency, carbon dioxide payback time, and price of the product gas from supercritical water gasification. Cellulose decomposes much more rapidly in supercritical water than in sub-critical water [40,41]. They concluded that this high reactivity can be used to decompose organic materials into gases without any pretreatment of drying feedstock. Therefore, Supercritical water gasification is considered a promising technology for the gasification of wet biomass since it does not require drying of feedstock beforehand. Separation of the gas and water occurs after complete gasification, cooling down and depressurization of the process. The waste remaining is inert and non-leachable.

5.6.9 Gasification and fuel reforming using HiTAC

Most of the HiTAC technology efforts have been for furnaces, boilers and waste fuel reforming [33]. Some of the near term applications include: (i) industrial furnaces (used in steel industry for melting, reheating, heat treatment and soaking, and for process heater, aluminum melters, petrochemical reforming, glass melting, drying, boilers, ceramic heater, and domestic boilers and heater), (ii) waste incineration/ waste thermal destruction of solid and liquid wastes including wastes produced from municipal, industrial, yard, chickens animals and farms. The technology is attractive for gasifying wastes, biomass fuels, and mixed wastes so that the gaseous fuel produced is clean and environmentally benign form of energy. High temperature steam gasification provides further benefits of higher heating value, higher hydrogen content, and high efficiency with minimum residue, (iii) fuel reforming and energy transformation to cleaner fuels for use in fuel cells, and other power, propulsion and energy conversion applications, (iv) power production using micro-gas turbines with the combustion of low to medium gas produced from biomass and wastes, (v) destruction of odors and certain pollutants, (vi) production of nano-powders and materials, nano-catalysts, nano-fluids, nano-sensors, and nano-related products, including energetic materials.

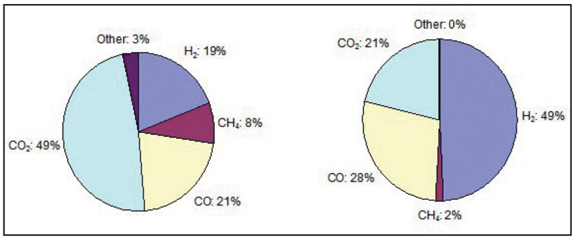


Figure 17: Chemical composition of the syngas produced with high temperature gasification of paper using steam at 700°C (left) and 1000°C (right).

5.6.10 High temperature steam gasification of wastes

The high temperature air combustion technology can also be used to produce very high temperature steam that can be used for coal, biomass and wastes and low grade fuels to produce clean syngas. Under favorable conditions very high molar concentrations of hydrogen can be produced from biomass and wastes. The tar produced with the use of high temperature steam is minimal. Sample results of the gas composition with paper as the solid fuel are given in Figure 17. The experimental results provided the influence of elevated gasifying agent temperature on hydrogen yield in the gas composition. In general the higher the steam temperature, the higher was the amount of hydrogen produced. This trend was true for all the solid fuels examined, including solid wastes, biomass, coal and agricultural wastes (rice husk, rice straw and corn cob). Methane gas production is an important component of syngas in the steam assisted gasification. Steam gasification at low temperatures favors methane production. In contrast at high gasification temperatures hydrogen yield increases as shown in the sample results in Figure 14. The HiTAC has been successfully demonstrated in Japan on a pilot plant fuel reformer to convert hydrocarbon fuels to

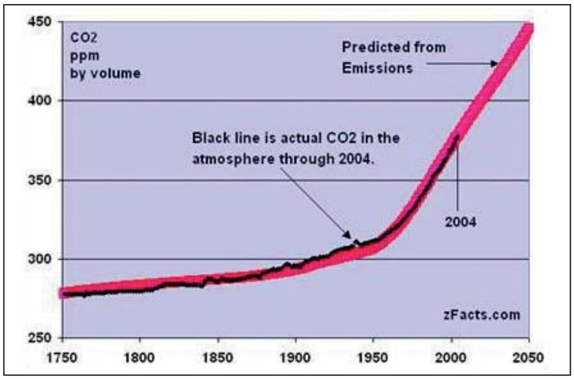


Figure 18: Increase in CO_2 emission levels since 1970 and projected to 2050.

hydrogen rich syngas using high temperature steam. The residue remained was only inert material so that it can be safely disposed. Lab scale tests showed that indeed the use of ultra-high temperature steam resulted in only inert material that is safe to dispose and can be used for the construction bed material for roads and building material.

6 Practical Aspects of Power Generation

A by-product from all fossil fuel power generation is the emission of pollutants including the emission of CO_2 greenhouse gas. Historic and geographical data indicate that temperature of the earth has been increasing since the onset of the industrial revolution in the 1800s. The concentration of CO_2 is high as compared to long term historic levels and has been increasing very rapidly with the onset of industrial revolution, see Figure 18. This correlates very well with the increased combustion of fossil fuels. The global temperature and CO_2 concentration correlate quite well as seen in Figure 19. Change in global temperature as small as 1K has profound effect on weather patterns, distribution of flora and fauna, and such geographical phenomena as ocean currents and the sea level. Some of the CO_2 capture approaches for power includes: (a) post capture (such as adsorption, absorption, hydrate based, cryogenics / refrigeration based), (b) oxy-fuel firing (external oxygen supply, integrated membrane-based, oxygen carriers), and (c) decarbonization (fuel reforming to achieve carbonized fuel, carbonate reaction from via combustion decarbonization). Innovative options will evolve with the focus on the carbon constrained world and from our focus on means to reduce the carbon emissions. The CO_2 mitigation options include: fossil fuel energy conservation increase in efficiency of the plant. Fuel switching from fossil to nuclear, renewables, and natural gas is favorable for CO_2 mitigation. In case the fuel switching and other CO_2 mitigation options are not favorable, the CO_2 generated from a power plant can be sequestrated by capturing it from the tail end of power plant and then sequestering it using either or some combination of sequestration approaches of: terrestrial ecosystems, geological storage in active oil beds, coal beds, depleted oil and gas wells, deep aquifers, mined caverns and salt domes.

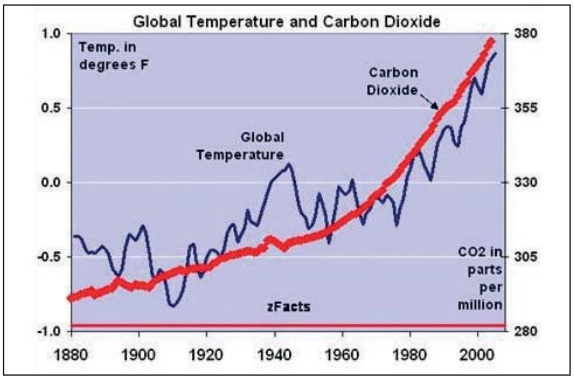


Figure 19: Global CO_2 concentration and temperature.

In 2006 global CO_2 emission from fossil fuel use has shown an increase of about 2.6%. China topped the international CO_2 emission table in 2006 for the first time in history. Total CO_2 emission in China increased by 8.7% in 2006 as compare to 1.4% in the USA and almost unchanged in the EU-15 countries (the EU-15 had a decrease of 0.8% CO_2 emission in 2005). Even with this increase, the average Chinese emits 3.5 tonnes of CO_2 per year, whereas Britons emit nearly 10 tonnes and Americans 20 tonnes.

6.1 *Pollutants emission*

The emissions from a power plant depend upon the type of fuel used and the design and operational conditions of the power system. The older units in the 1950's had no pollution control device while the 1990's unit had pollution control for particulate mater, NO_x, and SO_2. A schematic diagram of the 1950's and 1990's power plant is given in Figure 20.

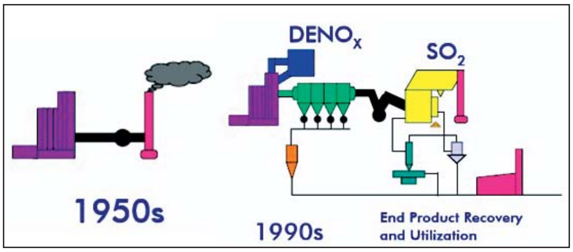


Figure 20: A schematic diagram of the power plant of the 1950s and 1990s.

Fluidized bed uses crushed coal for power generation. Here the bed is kept low temperature (below 900°C) and the bed contains calcium based sorbent material to capture SO_2 evolved during combustion. The NO_x emission is low since the combustion temperature in the bed is below the temperature at which thermal NO_x is formed. However, the emission of N_2O emission (a greenhouse gas that has more pronounced effect than CO_2 gas emission to the atmosphere) is a disadvantage since it is formed and propagates at low temperatures. Therefore one must determine a striking balance to determine favorable conditions for reducing N_2O emission and enhance sulfur capture.

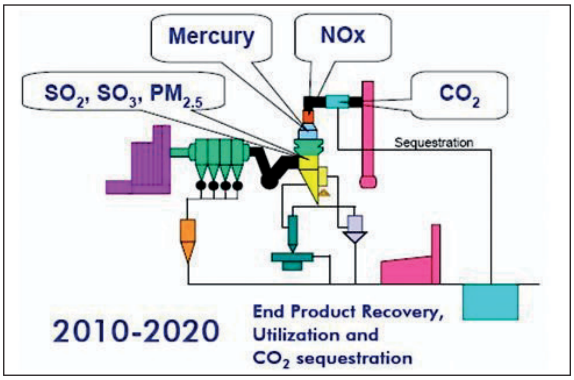


Figure 21: A schematic diagram of the future power plant with advanced pollution control including CO_2 capture and sequestration.

The criteria pollutants includes: NO_x, SO_x, HC, Mercury (Hg) and fine particles with particle size smaller than 10 microns (PM10) or even 2.5 microns and under (PM2.5). Staged combustion has been shown to be effective and mature technology to achieve low NO_x. However, problems exist on the carbon burnout during fuel rich pyrolysis of the coal that is used for low NO_x emission. Therefore, a better understanding of the physical and chemical transformations of coal, in particular the change in reactivity of char in the fuel rich high temperature pyrolysis region of the combustion chamber used for NO_x reduction. Selective catalytic reduction (SCR) technique is well established technology for post combustion clean up of NO_x from the flue gases. Low NO_x burners are available that can reduce the NO_x levels by more than 95%. The SOx control is usually obtained by Flue Gas Desulfurization (FGD). The technology most widely used today is wet scrubbing FGD to remove up to about 97% using Ca/S molar ratio of 1 to 1.5. In dry scrubbing FGD an alkaline slurry reagent in aqueous form is sprayed into the flue gas. The water is evaporated quickly and the reaction products are removed as dry powder. Dry FGD has the advantages of low cost and less water requirements. However, the disadvantages are lower capture efficiency (about 70 to 90%), reduced reagent utilization (1.1-1.6) and exclusion of limestone as reagent option. Other FGD options include ammonia scrubbing to produce ammonium sulfate that can be used as fertilizer and in cases when the sulfur content is very high, the SO_2 is oxidized to SO_3 and then subsequently to sulfuric acid.

Particulate matter removal technologies from the tail end of the power plant utilize fabric filters (bag houses) for large size particles and electrostatic precipitators for fine particles. This is also a mature technology to achieve 99.9% (or 3 nines) collection efficiency and results in emission levels of 0.01 to 0.03 lb/MBtu.

Mercury emissions can be obtained using powered activated carbon. Mercury capture efficiency has been shown to be 50 to 70 with ESPs and up to about 90% with fabric filters. The capture efficiency strongly depends on the form of mercury vapor in the flue gas. Chlorine in the coal or Bromine addition to coal greatly enhances the mercury capture. Thus co-combustion of fuels (for example coal and wastes such elements) is beneficial for enhancing mercury capture efficiency while simultaneously utilizing waste fuels without modifying the combustor.

It is clear that with the increased energy use and greater awareness of the harmful effects of pollutants from combustion one can only expect to see even more stringent air pollution control from the tail end of power plants. We expect control from larger size plants will occur first than small size plants. Emission of carbon dioxide will continue to be of greater concern to the society as the evidence of close correlation between global CO_2 concentration and temperature is very convincing. A schematic diagram of the future fossil fuel power plant of the 2020 is shown in Figure 21.

7 Conclusions

Various methods of power generation, including some recent advances in power generation are presented. With the continued developments very high efficiency thermodynamic efficiency can be achieved from fossil fuel combustion systems. Costs of coal and other solid fuels are favorable than clean natural gas. However, with the recent developments in gasification and other developments on integrated power systems, it is reasonable to achieve very high thermodynamic cycle efficiencies, close to 60%, with low pollution emission in the near future. Future large scale energy conversion systems are expected to have CO_2 capture technologies and sequestration so that one must seek innovative designs for advanced hybrid systems which can potentially offer very high efficiency and low pollution emission.

High temperature air combustion has shown significant potential of HiTAC technology. The HiTAC provides colorless distributed combustion, and under certain conditions green color and other flame colors. The flame size increases under HiTAC conditions. The emission of NO_x is very low at high temperatures and low oxygen concentration air as compared to normal combustion air at low temperatures. HiTAC flame gives low noise, high thermal field uniformity (better than 30°C to provide an isothermal reactor) in the furnace. HiTAC has been used in many countries worldwide with significant energy savings demonstrated in field test trails and in many practical systems. Fuel reforming using high temperature steam gasification of wastes, biomass and coals provides clean conversion of waste fuels and biomass to hydrogen-rich syngas.

Advanced gasification using high temperature steam (super-critical steam) offers good sound solution for the management of solid wastes with increased hydrogen production high energy recovery and much reduced residue. The residue produced is non-leachable so that this provides a good sustainable solution for the management of various kinds of solid wastes.

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