**Basic Environmental Engineering and Pollution Abatement**
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**Lecture – 53**
**Solid Waste and Hazardous Waste Management - 3**

Hello everyone. Now, we will discuss on the topic solid waste and hazardous waste management, part-3. And we will be focusing on the gasification.

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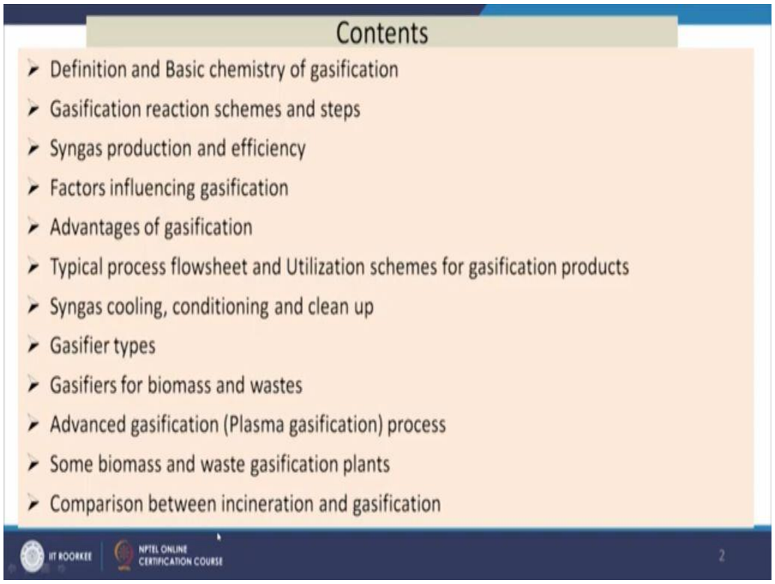


The contents are definition and basic chemistry of gasification, gasification reaction schemes and steps, syngas production and efficiency, factors influencing gasification, advantages of gasification, typical process flowsheet and utilization schemes for gasification products, syngas cooling, conditioning and clean up, gasifier types, gasifiers for biomass and wastes, advanced gasification plasma gasification process, some biomass and waste gasification plants, and comparison between incineration and gasification.

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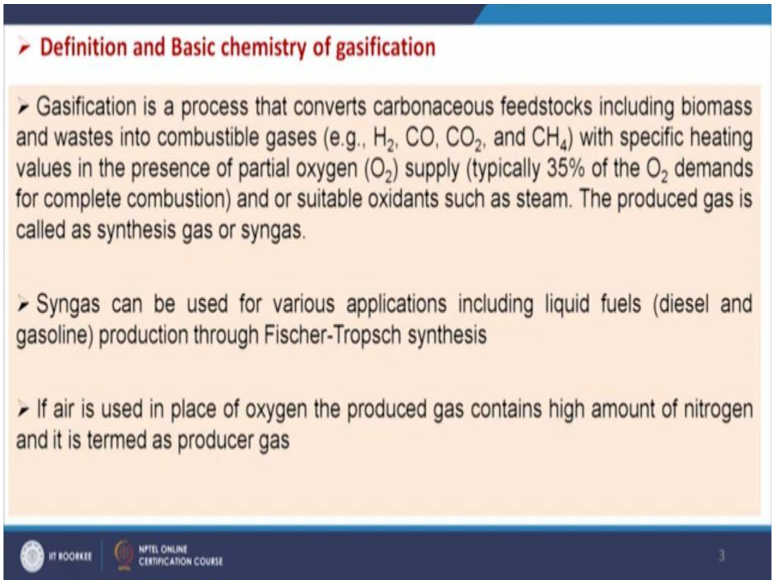


Now, we will see what the gasification is. So, unlike incineration, in this method, we will be providing a controlled amount of oxygen. So, feedstock will be there, controlled amount of oxygen and steam is required also for these gasification. But, if the feedstock contains very high amount of moisture, then the steam requirement may not be needed. So, gasification is a process that converts carbonaceous feedstocks, including biomass and waste into combustible gases containing hydrogen CO, $CO_2$, $CH_4$ basically, with specific heating values in the presence of partial oxygen supply.

Typically, 35 % of the oxygen demands for complete combustion, and or suitable oxidants such as steam; the produced gas is called as synthesis gas or syngas. When the waste and biomass is reacted with oxygen and steam; so this is called as the syngas. But, when the air will be used in place of oxygen, then nitrogen will also be available in the product; and that gas is called as producer gas. So, syngas can be used for various applications including liquid fuels, diesel and gasoline production through Fischer-Tropsch synthesis; so that is one advantage of this. So, we can get from solid fuel to liquid food also, through this route.

And if air is used in place of oxygen, the produced gas contains high amount of nitrogen; and it is termed as the producer gas. So, we will see the basic chemistry of the gasification process. So one, in this process, we have carbonaceous feedstock.

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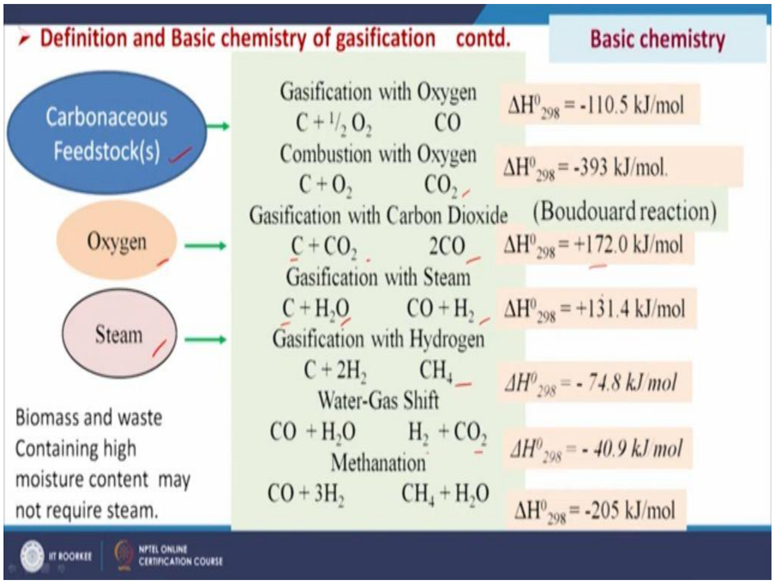


So, carbonaceous feedstocks and oxygen and steam will be needed; and somewhere steam may not be needed, when sufficient moisture is available in the feedstock itself. So, what will be the reactions? The elementary reactions which you can propose that

$C + ½ O_2 \rightarrow CO$.

The carbon monoxide is produced through these reactions, where $\Delta H^o_{298}$ is - 110.5 kJ/mol; and there may be some combustion; so, this reaction $C + ½ O_2$ that is CO; that is called gasification with oxygen. And combustion with oxygen that means complete combustion; that will be stoichiometric ratio of oxygen; so that is $CO_2$.

And gasification with carbon dioxide,

$C + CO_2, \rightarrow 2CO, \quad \Delta H^o_{298} = - 110.5$ kJ/mol

And then gasification with steam,

$C + H_2O \rightarrow CO + H_2, \; \Delta H^o_{298} = +131.4$ kJ/mol

And gasification with hydrogen. So, this hydrogen which is produced from this reaction, the gasification with steam; so that hydrogen can react with the char and can give us a methane.

$C + 2H_2 \rightarrow CH_4, \; \Delta H^o_{298} = - 74.8$ kJ/mol

These are the main reactions which are proposed to be involved in the gasification reactions. And there are some other reactions that is side reactions like

$CO + H_2O \rightarrow H_2 + CO_2$; $\Delta H^o_{298} =$ -40.9 kJ/mol

That is water gas shift reactions, and methanation reaction

$CO + 3H_2 \rightarrow CH_4 + H_2O$; $\Delta H^o_{298} =$ -205 kJ/mol

So, these are the different reactions which have been proposed to be available during the gasification; these are the elementary reactions; and ΔH values are also given for different reactions. So, this reaction, gasification with carbon dioxide that is also called Boudouard reaction; and this is endothermic reaction. So, it is clear from this that both endothermic and exothermic reactions take place during the gasification process.

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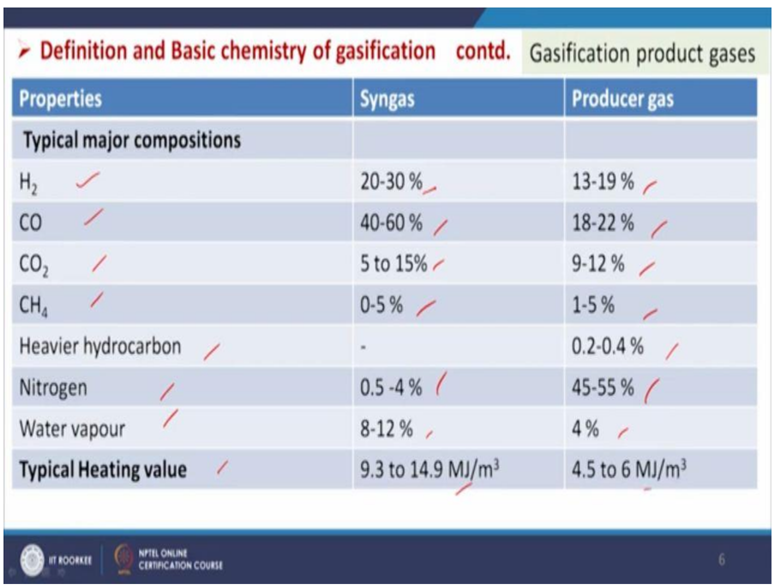

➤ Definition and Basic chemistry of gasification contd. Gasification product gases

| Properties | Syngas | Producer gas |
|---|---|---|
| **Typical major compositions** | | |
| $H_2$ | 20-30 % | 13-19 % |
| CO | 40-60 % | 18-22 % |
| $CO_2$ | 5 to 15% | 9-12 % |
| $CH_4$ | 0-5 % | 1-5 % |
| Heavier hydrocarbon | - | 0.2-0.4 % |
| Nitrogen | 0.5 -4 % | 45-55 % |
| Water vapour | 8-12 % | 4 % |
| **Typical Heating value** | 9.3 to 14.9 MJ/m$^3$ | 4.5 to 6 MJ/m$^3$ |



And we have also discussed that if we use oxygen, we will get syngas; and if we use air, we will get producer gas. Now, we will see the difference in competition between these two gas types. So, type that is typical major competitions like say hydrogen, CO, $CO_2$, $CH_4$, heavier hydrocarbon, nitrogen, water vapor; and also the typical heating value, if we compare. So, hydrogen in case of seam gas 20 to 30 %; whereas, producer gas 13 to 19 %. And CO, 40 to 60 %; here 18 to 22 %. And $CO_2$, 5 to 15; where it is 9 to 12; and $CH_4$, 0 to 5; here 1 to 5 %.

Heavier hydrocarbon, it is present in producer gas; and nitrogen content is very high, in case of producer gas; but, here it is less.

And water vapour is also here 8 to 12 % for syngas and 4 % around for producer gas. And typical heating value is 9.3 to 14.9 $MJ/m^3$; whereas for producer gas, it is 4.5 to 6 $MJ/m^3$. So, these are the different properties of the syngas and producer gas.

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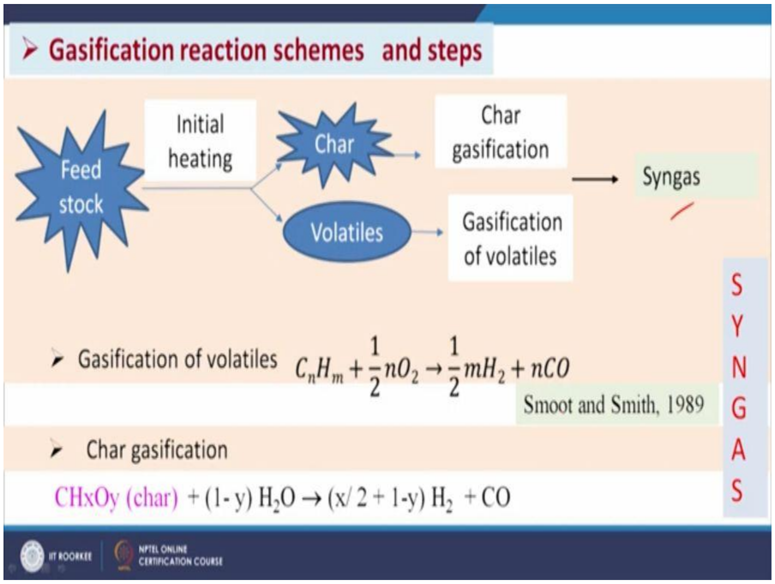


So, accordingly you can select their application. Now, what elementary reactions we have proposed? We have seen in the previous slide for the gasification reaction that may not be exactly representing the overall reactions. Because, the feedstock will also contain ash material sulphur, and other materials also nitrogen etc. which was not considered during those elementary reactions. So, people try to develop some new mechanism or reaction schemes to explain the gasification reactions; like say, feedstocks is initially heated, and it is proposed that the char and volatiles are produced in the first step.

Then, in the second step both char and volatiles are gasified. So, gasification of char and gasification of volatiles takes place, and gives the syngas; so when the two intermediate products we are getting. So, different researchers proposed the different reaction schemes for the production of the syngas through these volatiles and char. For example, for gasification of volatiles like

CnHm + ½ $nO_2 \rightarrow$ ½ $mH_2$ + nCO.

And for char gasification,

CHxOy (char) + (1-y) $H_2O \rightarrow$ ( x/2 + 1 – y) $H_2$ + CO.

So, these are different types of mechanism or schemes have been proposed by some researchers, Smoot and Smith in 1989.

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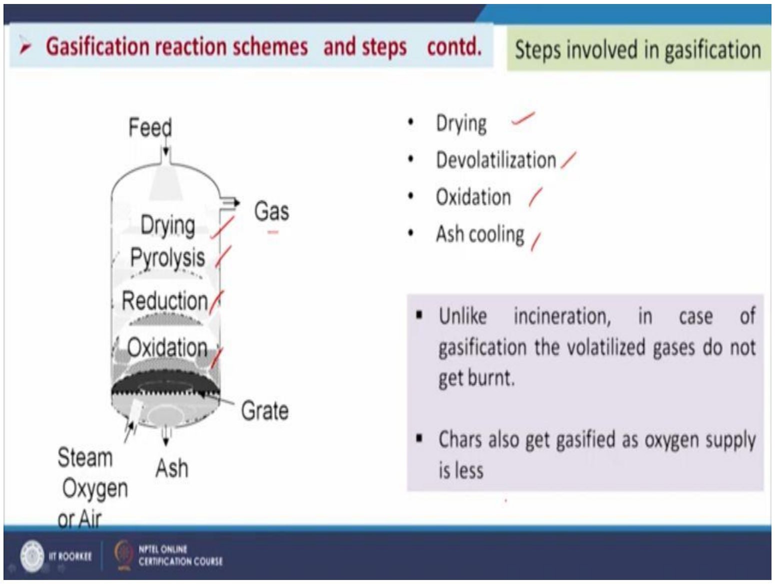


After that some more comprehensive mechanism or schemes have been proposed by some other researchers. Those can be used for more comprehensive understanding of the process which may be available in other references. So, now we will see what are the steps involved in a gasification process? Basically in gasification process like incineration process, here also the drying, divolatilization, oxidations and ash cooling are also taking place. So, drying, pyrolysis, reductions, oxidation all those reactions take place during the gasification.

We have also mentioned in our previous slide as well. So, this is one example of say fixed bed gasifier. So, our feed is coming from the top and from the water steam, and oxygen or air is sent. So, that is a grate where the solids feedstock will be stored. Basically, after combustion, the ash will be coming at the bottom and some feed will also be available here. The oxygen is provided here maximum oxygen is there; so, feed will be oxidized initially. When the gas stream will goes up, the availability of oxygen will reduce; so reduction will start. Oxidation will be subsided; and then, then reduction will be started.

And then there will be only heating, so pyrolysis and then only drying moisture removal; and gas will be going out from the top. So, this is one scheme for the gasifications in the reactor. And drying, divolatilization, oxidation and ash cooling are very important, where the ash is coming out from this through the grate, the ash will come down. And it will be collected, and it will be cooled and managed through a proper route. And unlike incineration in case of gasification, the volatilized gases do not get burned. So, this gas which is volatilized here, that does not get burned; that is why the CO and $H_2$ containing syngas we get.

And chars also get gasified as the oxygen supply is less; we have already discussed in the previous slide also.

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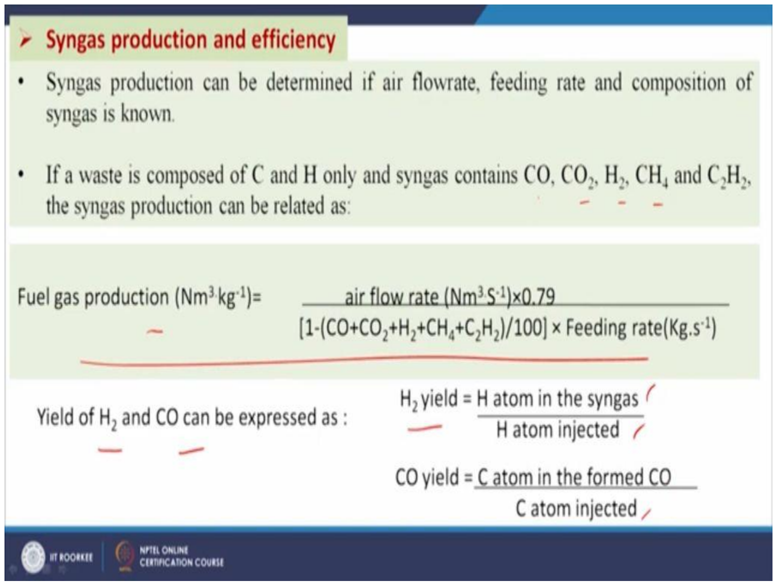


Now, we will see how can we predict the fuel gas production? If we know the rate of feedstocks utilization, and if we know the air flow rate; then, on that basis, we can calculate the fuel gas production that is say producer gas production rate, normal meter cube per kg. So, syngas production can be determined if airflow rate, feeding rate, and composition of syngas is known. If a wastage composed of carbon-hydrogen only, and syngas content CO, $CO_2$, $H_2$, $CH_4$ and $C_2H_2$, the syngas production can be related with this formula. So, this formula is derived on the basis of nitrogen balance.

$$\text{Fuel gas production}\left(\frac{\text{Nm}^3}{\text{kg}}\right) = \frac{\text{Air flow rate}\left(\frac{\text{Nm}^3}{\text{s}}\right)}{[1-(CO+CO_2+H_2+CH_4+C_2H_2)/100]\times \text{Feeding rate}\left(\frac{\text{kg}}{\text{s}}\right)}$$

You see what are the nitrogen present in the air flow rate into 0.79; assuming that 79 percent is nitrogen, so that is the nitrogen present in the air. So, that nitrogen will be available in fuel gas. The nitrogen content in the fuel gas; that is nothing but the fraction of nitrogen present in it and then feed rate. So, per unit feed rate, what is the fuel gas production that you can get by this expression?

So, that we are that way this expression is coming by the nitrogen balance in air, and in the syngas. And we also predict or calculate the yield of hydrogen and CO like this expression.

$$H_2 \text{ Yield} = \frac{\text{H atom in the syngas}}{\text{H atom injected}}$$

$$\text{CO Yield} = \frac{\text{C atom in the formed CO}}{\text{C atom injected}}$$

So, that way we can calculate the yield of CO and $H_2$.

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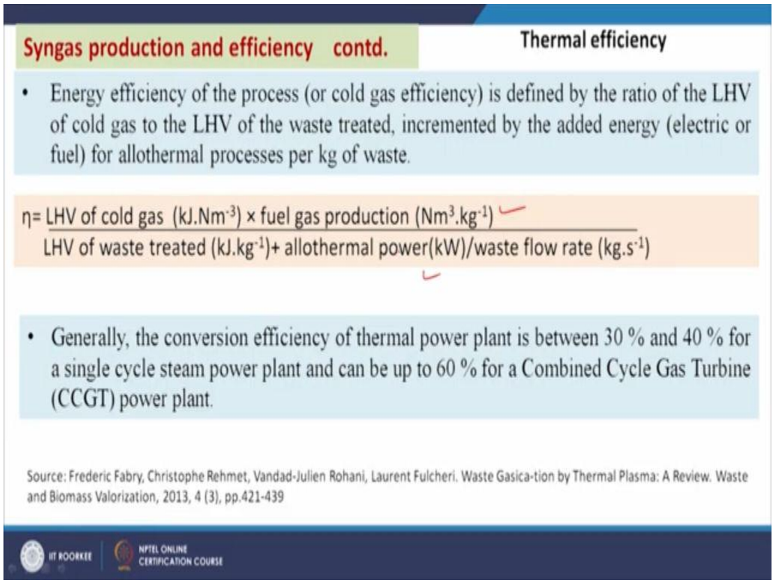


Now, we will see the thermal efficiency. In case of gasification, energy efficiency of the process; or cold gas efficiency is defined by the ratio of the LHV of cold gas to the LHV of waste treated. LHV is low heating value and incremented by the added energy that is electric or fuel, for allothermal processes per kg of waste.

$$\eta = \frac{\text{LHV of cold gas } (\text{kJNm}^{-3}) * \text{fuel gas production } (\text{Nm}^3\,\text{kg}^{-1})}{\text{LHV of waste treated } (\text{kJkg}^{-1}) + \text{allothermal power (kW)} / \text{ waste flow rate} (\text{kg.s}^{-1})}$$

So, this allothermal power that means the additional energy which is needed for the conversion of the feedstock to the product. So, this is the relationship of the energy efficiency. Generally, the conversion efficiency of thermal power plant is between 30 % and 40 % of a single cycle steam power plant; and can be up to 60 % for a combined cycle gas turbine power plant. So, we have either a combined cycle or bottoming cycle or topping cycle. So, there are different types of thermodynamic cycles which are applicable for the recovery of energy in a thermal power plant.

So, these are the typical efficiency for different types of thermodynamic cycles applicable in the thermal power plant.

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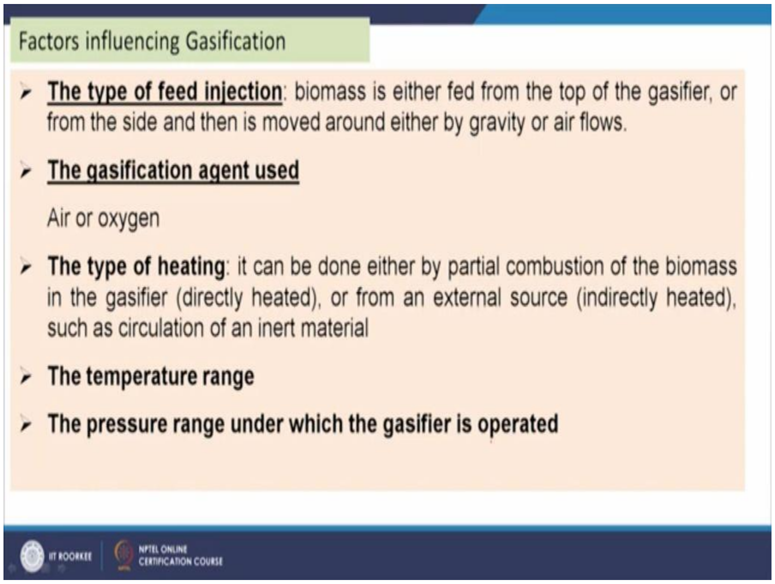


Now, factors which influence the gasification that we will discuss. So, the type of feed injection; what type of feed we are using that will influence the syngas production. The gasification agent used whether we are using air or oxygen. Type of heating, it can be done either by partial combustion of the biomass in the gasifier, that is directly heating; or from an external source indirectly heating such a circulation of an inert material. The temperature range also influences the performance of the process. The pressure range under which the gasifier is operated; that is also important for the performance of the gasifier.

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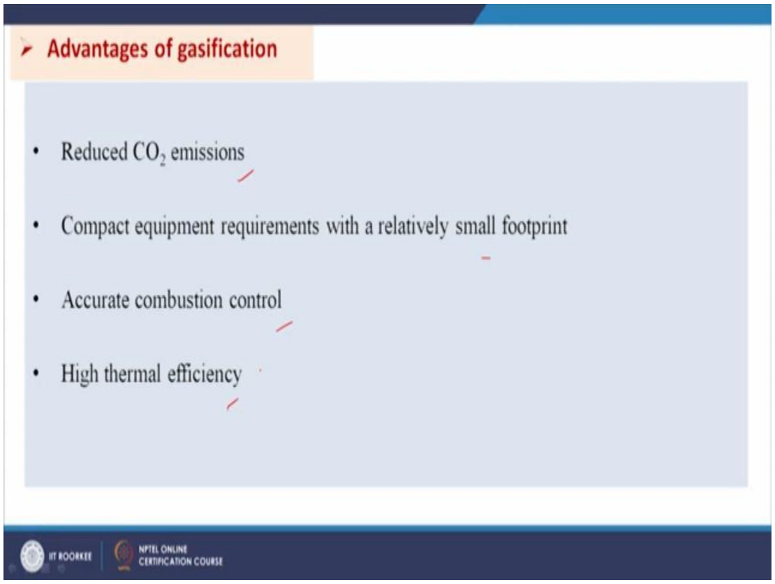


And this gasification process has some advantage over the incineration process, like say reduced carbon dioxide emissions, and then compact equipment requirements with a relatively small footprint, accurate combustion control and high thermal efficiency. So, these are the reasons why the gasification is preferred; moreover, the products can be used for different applications.

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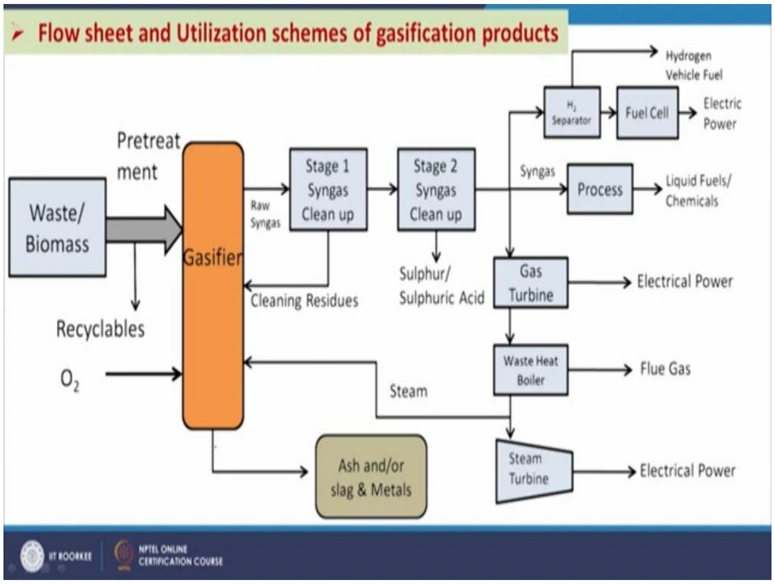


Now, we will see the flow sheet and utilization schemes of gasification products. So, we have waste and biomass. So, that will be after pretreatment going to gasifier; that means some pretreatment is required to make it suitable for applications in the gasifiers. That means it may be needed to densify, to increase its density, it may be required to grind it to have a particular particle size; so, that can be needed for the effective operations in the gasifier. And then, we will be sending the oxygen or if needed steam, so then the gasification will take place; so, syngas will go out.

So, if we supply oxygen, then we will get syngas. So, syngas will be having some particulate matters, so that stage one clean syngas cleanup, so that particulate removal; so cleaning residues is given here. Then, second step syngas cleanup, because of the acid gas removal. So, this also tar removal can also taking place here in this first step; and the second step the acid gas removal that is $H_2S$ removal. And then, this can be used for liquid fuels or chemical synthesis; or, it can be used for hydrogen separation. And hydrogen can be used in different applications, including fuel cells, and can be converted to electrical power.

Or, it can be processed to the gas turbine, so that we can get electrical power, and followed by wasted boiler; so flue gas you can get. And it can be passed to the steam turbine using some additional fuel; it can be going for steam turbine and the electricity production can take place. So, these way the electricity can be produced from the syngas, and then the content steam is coming here from the waste heat boiler. So, steam either can come here or this can be going to steam turbine for electrical power production. And in the gasifier, we have some residue that is ash or slag or metals that has to be managed in a proper way.

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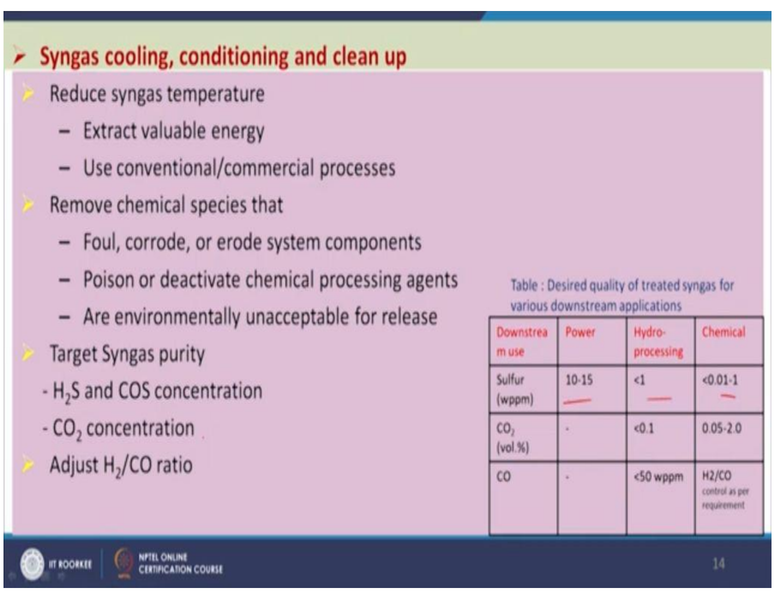

Now, syngas cooling and conditioning and clean up. So, syngas which is generated that will be at higher temperature; and it will be containing particulate, it will be containing say acid gases. So, we need to remove this, because different downstream application requires a certain level of purification. So, if we see here, so different downstream applications like say power, hydro processing and chemical applications. So, here sulphur requirement is within this limit; for chemical, more purity is required; but for power applications, less sulphur removal is needed.

And carbon dioxide, similarly for power there is no requirement; but for hydro processing, more purity is needed. So, less than 0.1 volume % and 0.05 to 2 volume %, carbon dioxide is needed for chemical synthesis. And CO similarly should be less than 50 wppm, and $H_2$/CO control as per requirement for the type of chemical we are interested to produce. So, this table clearly indicates that the syngas requires some cleanup for its downstream application. And the clean up is needed to reduce syngas temperature, extract valuable energy, use conventional and commercial processes that can be used in commercial industrial processes.

This also removed chemical species that foul, corrode, or erode system components, poison or deactivate chemical processing agents, and are environmentally unacceptable for release. And target syngas purity $H_2S$ and COS concentration, $CO_2$ concentration, and these are as for this table. And $H_2$ by CO ratio has to be adjusted for the application in chemical synthesis route.

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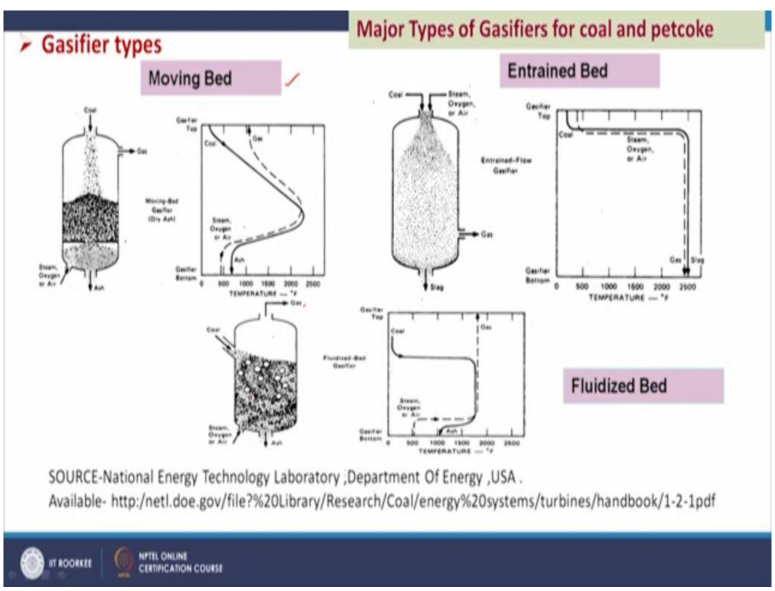

Now, major types of gasifiers for coal and petcoke. So, biomass and waste are basically low dense materials highly reactive materials; but coal and petcoke are less reactive and dense material, the carbon content is higher in this feedstock. So, for the gasification of this type of feedstocks require higher temperature. And we also know that petcoke is produced as the residue in the petroleum refinery; so that is a noised material waste product. So, this is also important feedstock or waste material for the production of energy. So, if we see different types of reactors which we have used for the gasification of coal and petcoke, then we see those are basically moving bed or fixed bed.

Both are same some books, it is mentioned as moving bed; and some books, it is called as fixed bed. Some is fluidized bed and another is your entrained bed. So, these three basic types of reactors have been used in literature for the gasification of the petcoke and coal. This is your fixed bed or moving bed. So, why moving bed? So, this is a grate and then the coal is coming from the top; and from the bottom, steam and oxygen air and is entering. And from the top gas is going out, ash is getting out, which is passing through the grate, and then it is coming through this the bottom part.

So, here thus material is fixed here, the bed is fixed, the coal is coming from the top; and from the bottom, the ashes are going out. So, this is this this is a fixed bed. why it is a moving bed? The coal is moving from top to bottom, so that is also this is a moving bed also. But, in fluidized bed, the coal is put from the top; and from the bottom steam, oxygen and air is sent. And then from the top again the gas is going. But, in entrained bed coal, steam, oxygen, air all are entering at the top; and from the bottom, the slag; and from the bottom side, we are getting the gas.

So, if we see, when the oxidation is there, then there will be the maximum temperature. So, in this type of reactions along the height, if we take the temperature, then maximum temperature will be the middle of that, will be around 1800 $^oC$. So, this is the maximum temperature. But that in this case, in entrained bed throughout the length, we are getting high temperature; and in the fluidized bed, we are getting maximum temperature at this part, So, that these are the different temperature distribution in different type of gasifiers.

So, the type of gasifiers will help to get different type of temperature distribution along the length of the gasifier. And that will also influence the performance of the gasifier. And it can also help us to decide which type of gasifier will be more suitable for handling what type of feedstocks. Like say for entrained bed, we are getting the high temperature throughout the whole length. So, if the material is less reactive, then also those material can be suitable here for gasification.

That is why, petcoke is more suitable here; but, for biomass and waste, so since the materials are highly reactive and less dense; so we do not need this much of high temperature and this type of arrangement. So, fluidized bed or fixed bed can be a suitable option.

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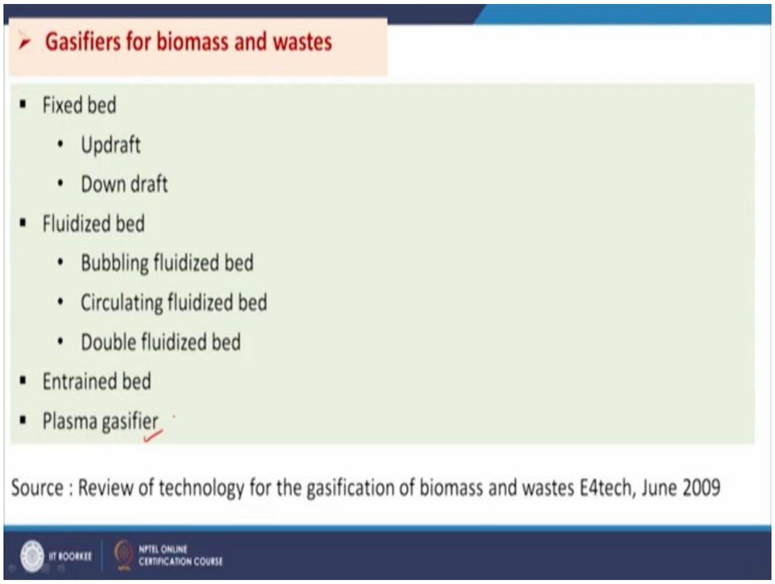


Now, gasifier for biomass and waste, if we see basically fixed bed fluidized bed have been used; entrained bed has also been used, and another gasifier that is plasma gasifier has also been reported. So, fixed bed are basically updraft and downdraft.

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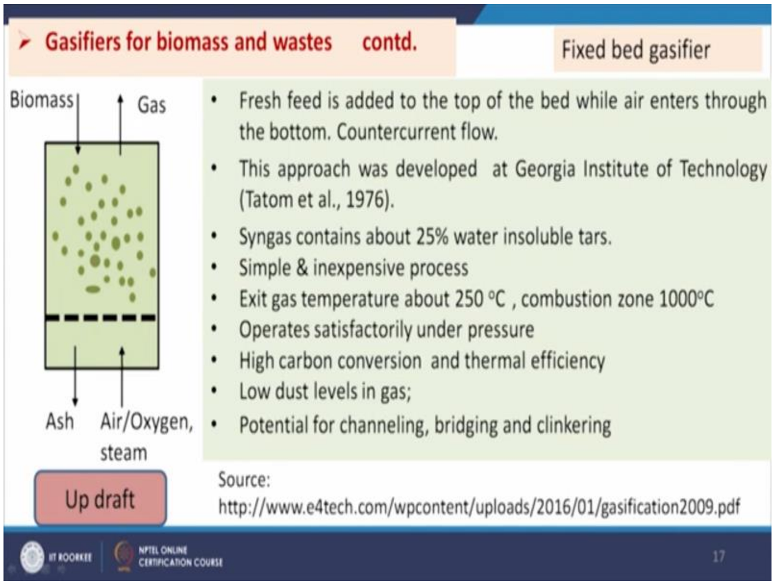


So, this is our updraft type. So, biomass is entering from the top and from the bottom we are sending air or oxygen and steam; and then gas is going out from the top; and from the bottom, we are getting the ash. So, this fresh feed is added to the top of the bed, while air enters through the bottom; so countercurrent flow. So, this approach was developed at Georgia Institute of Technology; and syngas contains about 25 % water insoluble tars. Simple and inexpensive process; so this is the main disadvantage that it contains good amount of tar in the syngas.

And exit gas temperature about 250 $^oC$, combustion zone 1000 $^oC$; operates satisfactory under pressure, high carbon conversions and thermal efficiency, low dust levels in gas, potential for channeling, bridging and clinkering. Then, we see the downdraft.

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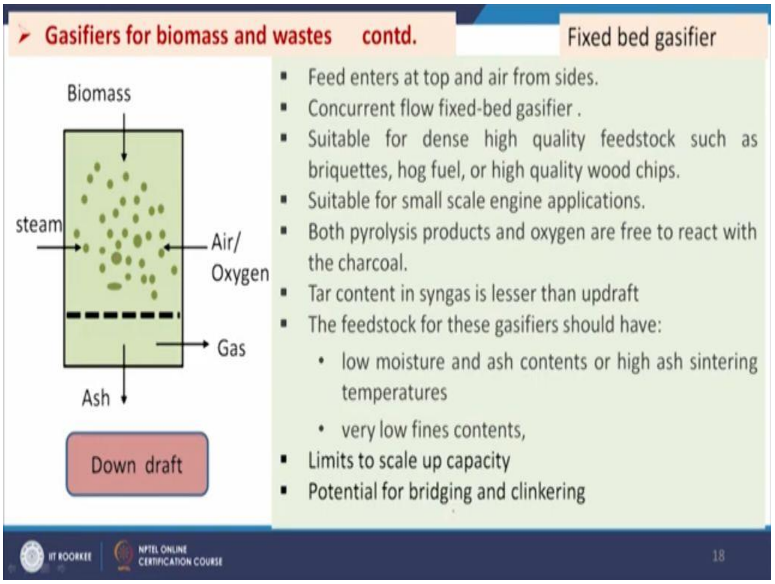


So, in that case, biomass from the top and air oxygen from the side. So, it is gas is also from the bottom part; so that is a downdraft, ash is coming from the bottom and the steam is also from the side. So, feed enters at the top and air from the sides. Concurrent flow fixed-bed gasifier; both are in the same direction, solid and the oxidizing agent. So, suitable for dense high quality feedstocks such as briquettes, hog fuel, or high quality wood chips, suitable for small scale engine applications. Both pyrolysis products and oxygen are free to react with the charcoal. Tar content in syngas is lesser than updraft; so, updraft has more char content than the downdraft gasification.

And the feedstock for these gasifiers should have low moisture and an ash content, or high ash sintering temperatures, very low fines contents, limits to scale up capacity, and potential for bridging and clinkering.

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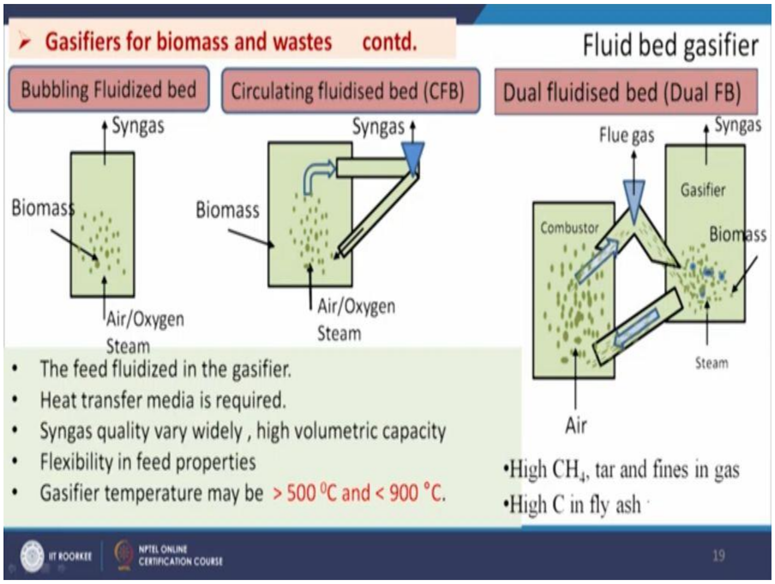


Now, we will see the fluidized bed gasifier. So, here again the biomass from the side, and from the bottom air or oxygen, steam; and from the top, syngas is going out. So, it is bubbling fluidized bed. And circulating fluidized bed so, the air or oxygen velocities maintained in such a way that some solid is also carried over with the syngas, and those are settled and recycled. So, that is circulating fluidized bed. And dual fluidized bed is here fluidized bed, and that is your bubbling and circulating both actions are available in this type of reactor. So here, this is combustor and this is gasifier.

So, then air is sent here in the first part, and then second part we are sending the steam. So, configuration is totally different from other two. So, this is dual fluidized bed, gasifier is also have been reported in literature. And the feed fluidized in the gasifier, the heat transfer media is required in this case, when it is going out. So, we need basically some sand or some other solids, so which helps for the quick heat transfer purpose. Syngas quality, vary widely, high volumetric capacity, flexibility in feed properties; and gasifier temperature may be greater than 500 $^oC$ and less than 900 $^oC$.

So, this is some salient features of this fluidized bed gasifier. And in this case we get high $CH_4$ tar and fines syngas, and high carbon in fly ash. These are the negative point.

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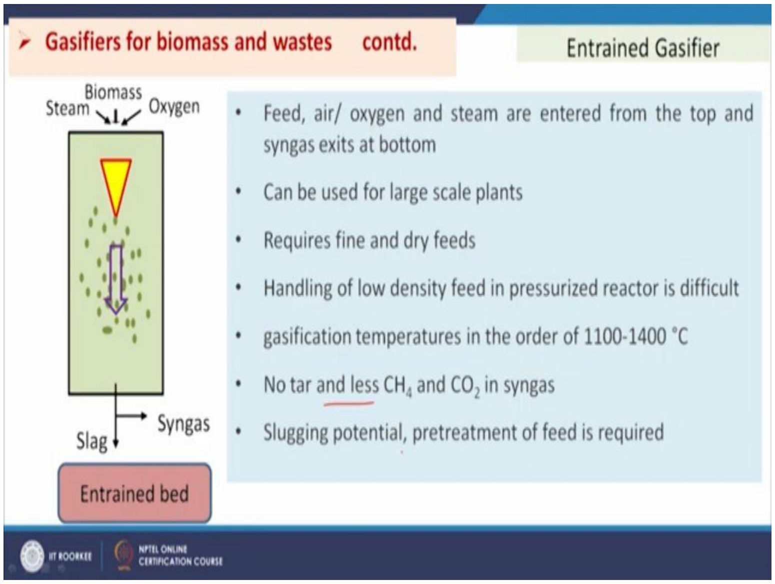


Then, entrained bed gasifier. So, like the petcoke gasifier, biomass, oxygen, steam is sent from the top; and from the side, we will get the syngas; from the bottom we will get the slag or ash. So, feed, air or oxygen and steam are entered from the top and syngas exits at bottom, can be used for large scale plants, requires fine and dry feeds. So, the fine feeds are needed for this purpose. Handling of low density feed in pressurized reactor is difficult. Gasification temperatures in the order of 1100 to 1400 $^oC$, no tar and less methane and $CO_2$ in syngas.

So, this is the one major advantage of it and slugging potential, pretreatment of feed is required. So, since the temperature is very high, the acid may be in slugging stage; and that can be a problem. And temperature of heat is also high; so that is the disadvantage of it.

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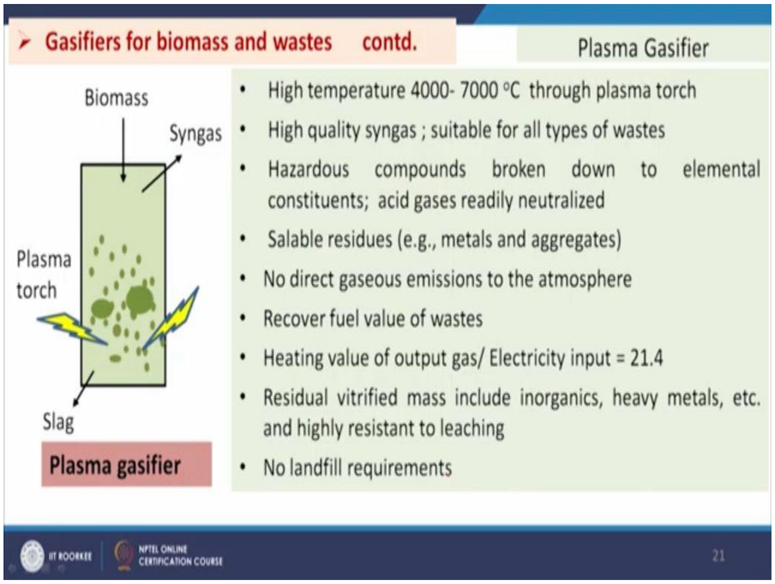


Another type of gasification is plasma gasification or plasma gasifier, which is used for the gasification of the biomass and waste. So, here high temperature is regenerated that is 4000 to 7000 $^{o}$C through plasma torch. High quality syngas can be obtained. This plasma gasification can be suitable for all types of waste. Hazardous compounds are broken down to elemental constituents; acid gases readily neutralized. So, salable residues like metals and aggregates, those can be having some market value; and no direct gaseous emissions to the atmosphere.

Recover fuel value of wastes, heating value of output gas or like electricity input. This ratio if we take heating value of output gas by electricity input that is equal to 21.4; and residual vitrified mass include inorganics, heavy metals, etc. and highly resistant to leaching, no landfill requirements. So, these are the some advantage of this plasma gasifiers. And what the plasma is?

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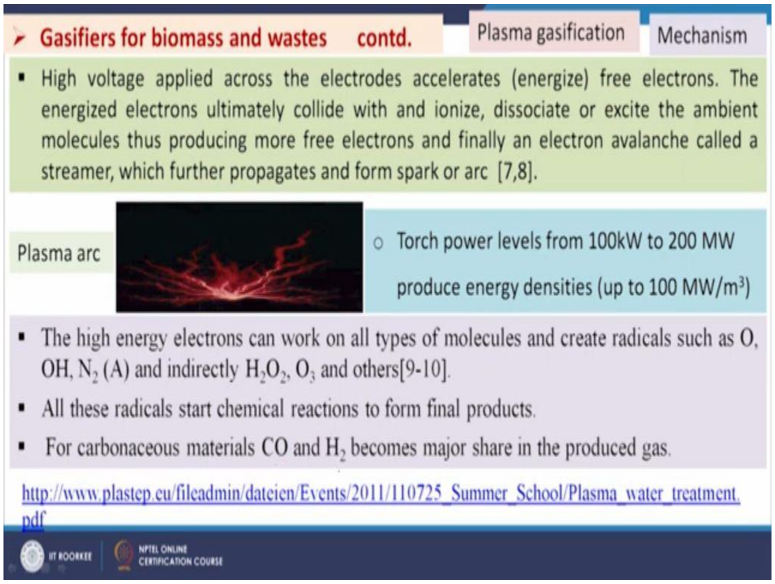


If you know that thundering process is one of the example of natural plasma formation. When high voltage is applied across the electrodes, it accelerates free electrons. The energized electrons ultimately collide with an ionize dissociate or excite the ambient molecules, thus producing more free electrons. And finally, an electron avalanche called a streamer, which further propagates and form a spark or arc; so this is a plasma arc. So, torch power levels from 100 kW to 200 MW; and produce energy densities up to 100 $MW/m^3$.

The high energy electrons can work on all types of molecules and create radicals such as this oxygen radical, OH radical, nitrogen and indirectly $H_2O_2$, $O_3$ and others. So, all these radicals start chemical reaction to form final products. For carbonaceous materials CO and $H_2$ becomes a major share in the produced gas, in case of gasification.

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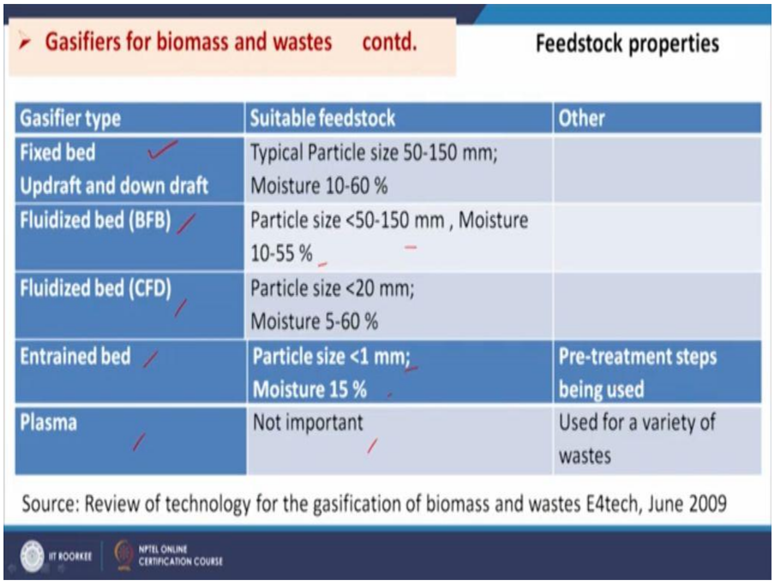


| Gasifier type | Suitable feedstock | Other |
|---|---|---|
| Fixed bed Updraft and down draft | Typical Particle size 50-150 mm; Moisture 10-60 % | |
| Fluidized bed (BFB) | Particle size <50-150 mm , Moisture 10-55 % | |
| Fluidized bed (CFD) | Particle size <20 mm; Moisture 5-60 % | |
| Entrained bed | Particle size <1 mm; Moisture 15 % | Pre-treatment steps being used |
| Plasma | Not important | Used for a variety of wastes |



Now, we will see the difference in the properties of feedstocks for different types of gasifiers. Like say, fixed bed gasifier, fluidized bed gasifier; that is bubble column and bubbling fluidized bed, and circular fluidized bed, entrained bed and plasma. So, you see the typical particular size is 50 to 150 mm, and moisture content 10 to 60 % for fixed bed gasifier; whereas, for fluidized bed, particle size less than 50 to 150 mm, moisture content 10 to 55 %. And fluidized bed circulatory, the particle size less than 20 mm and moisture 5 to 60 %.

For entrained bed, particle size less than 1 mm and moisture 15 %. So, in case of moisture, entrained bed the particle size requirement is the minimum; so the smallest particle size are required. But, for plasma these are not important. So, plasma gasification can be used for variety of wastes. And for entrained bed gasifier, some pretreatment steps are needed; because thus very small size is required.

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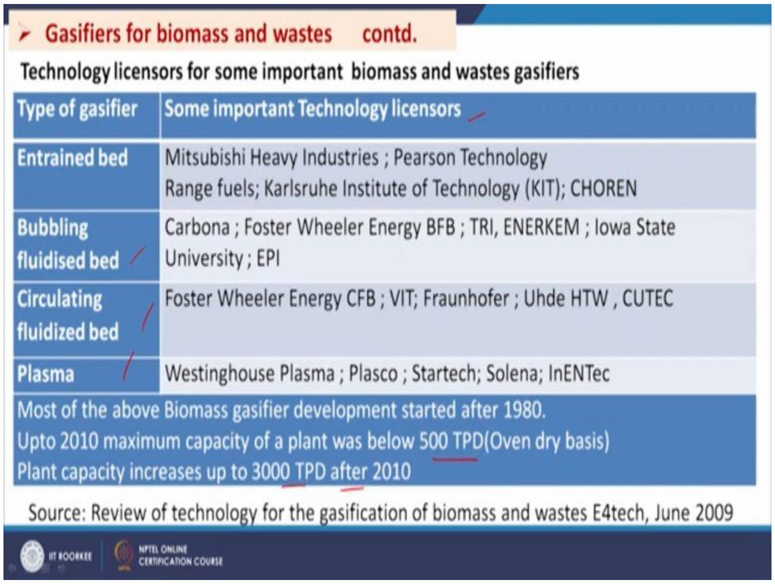
Gasifiers for biomass and wastes contd.

Technology licensors for some important biomass and wastes gasifiers

| Type of gasifier | Some important Technology licensors |
|---|---|
| Entrained bed | Mitsubishi Heavy Industries ; Pearson Technology Range fuels; Karlsruhe Institute of Technology (KIT); CHOREN |
| Bubbling fluidised bed | Carbona ; Foster Wheeler Energy BFB ; TRI, ENERKEM ; Iowa State University ; EPI |
| Circulating fluidized bed | Foster Wheeler Energy CFB ; VIT; Fraunhofer ; Uhde HTW , CUTEC |
| Plasma | Westinghouse Plasma ; Plasco ; Startech; Solena; InENTec |

Most of the above Biomass gasifier development started after 1980.
Upto 2010 maximum capacity of a plant was below 500 TPD(Oven dry basis)
Plant capacity increases up to 3000 TPD after 2010

Source: Review of technology for the gasification of biomass and wastes E4tech, June 2009

These are some important technology licensors for different types of gasifiers, like entrained bed gasifiers, bubbling fluidized bed, circulating fluidized bed, plasma gasifiers. So, you see here different technology licensors. And most of the above biomass gasifier, development started after 1980. And upto 2010, maximum capacity of a plant was below 500 TPD, oven dry basis. And plant capacity increases up to 3000 TPD after 2010. So, this has we have got it from this reference.

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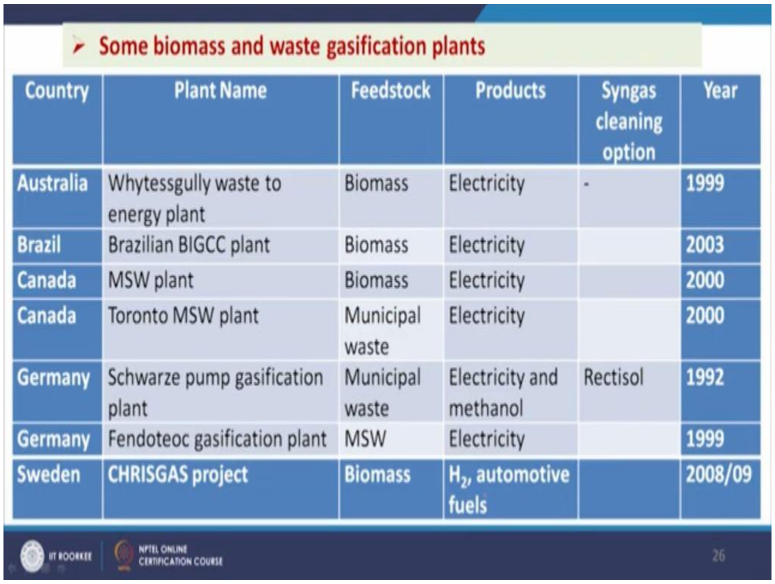
Some biomass and waste gasification plants

| Country | Plant Name | Feedstock | Products | Syngas cleaning option | Year |
|---|---|---|---|---|---|
| Australia | Whytessgully waste to energy plant | Biomass | Electricity | - | 1999 |
| Brazil | Brazilian BIGCC plant | Biomass | Electricity | | 2003 |
| Canada | MSW plant | Biomass | Electricity | | 2000 |
| Canada | Toronto MSW plant | Municipal waste | Electricity | | 2000 |
| Germany | Schwarze pump gasification plant | Municipal waste | Electricity and methanol | Rectisol | 1992 |
| Germany | Fendoteoc gasification plant | MSW | Electricity | | 1999 |
| Sweden | CHRISGAS project | Biomass | $H_2$, automotive fuels | | 2008/09 |

And now, we will see the different plants, some biomass and waste gasification plants around the globe. So, Australia, Brazil, Canada, Germany, Sweden, different countries, different plant, different feedstocks, different products; and syngas cleaning options are also different and year of commissioning are also provided in this slide.

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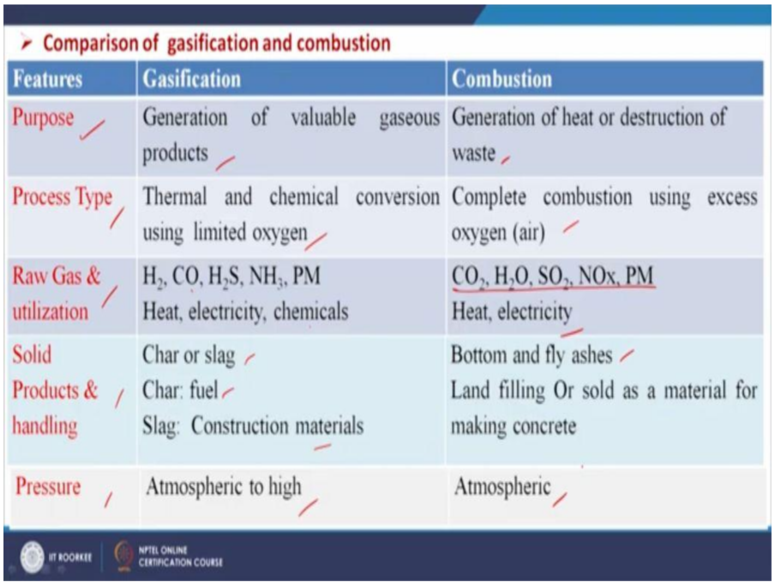

➤ Comparison of gasification and combustion

| Features | Gasification | Combustion |
|---|---|---|
| Purpose | Generation of valuable gaseous products | Generation of heat or destruction of waste |
| Process Type | Thermal and chemical conversion using limited oxygen | Complete combustion using excess oxygen (air) |
| Raw Gas & utilization | $H_2$, CO, $H_2S$, $NH_3$, PM<br>Heat, electricity, chemicals | $CO_2$, $H_2O$, $SO_2$, NOx, PM<br>Heat, electricity |
| Solid Products & handling | Char or slag<br>Char: fuel<br>Slag: Construction materials | Bottom and fly ashes<br>Land filling Or sold as a material for making concrete |
| Pressure | Atmospheric to high | Atmospheric |

And here we will see the difference between the gasification and combustion. So, if we take some criteria, that is purpose, process type, raw gas and utilization, solid products and handling and pressure; then you see the for gasification generation available gaseous products, it is our purpose. And for combustion, generation of heat or destruction of waste is our main purpose and; thermal and chemical conversion using limited oxygen is our process type. And here we get complete combustions with excess air or oxygen. And then raw gas and utilization, you see these are the raw gas which contains $H_2$, CO, $H_2S$, $NH_3$, particulate matter and heat, electricity, chemicals we can get from it.

Whereas, in this case, there is no CO basically, and $NH_3$ is converted to NOx, PM, $SO_2$ etc. is there; $H_2S$ is converted to a $SO_2$. So, these are the basic difference in these combustions and gasification process; and it is only used for heat and electricity. It cannot give us any chemicals or hydrogen; so solid products and handling. Then, char or slag is produced in this case; so char is fuel and slag is construction materials. Here we can get bottom and fly ashes. So, land filling or sold as a material for making concrete; and pressure atmospheric to high pressure. The gasification reaction can take place, but combustion takes place in atmospheric pressure. So, up to this in this class, thank you very much for your patience.