

because of the low biomass hold-up in the bed. These systems are, however, most appropriate for biomass whose particle sizes range from 0.1 to 1 cm (see Figure 13.29) and are normally suitable for small applications comprising high carbon loss with entrained ash. The loss of fluidization due to sintering of ash is a common problem, which can be controlled by maintaining higher bed temperatures of the order of 800–900 °C. Sintering occurs due to the agglomeration of alkali metals from biomass ash with the silica in the sand.

In the entrained flow gasifier reactors, no inert material is present but finely reduced fuelstock is required. They are normally used for large-capacity (30 tonnes/hour) fast-circulating bed gasifiers for the paper and pulp industry.

Tables 13.12 and 13.13 give typical operational data and the producer gas composition and quality in different gasifier reactors. The performance characteristics of various air gasifier reactors are compiled in Annex 1.

## Guidelines for designing downdraft gasifiers

This section gives a general review of the design characteristics of an Imbert type downdraft gasifier on the basis of the Swedish experience.

The design of an Imbert type downdraft gasifier is based on specific gasification rate, also called the hearth load  $G_H$ . It is defined as the amount of producer gas to be obtained per unit cross-sectional area of the throat, which is the smallest area of cross-section in the reactor. It is normally expressed in terms of  $\text{Nm}^3/\text{h cm}^2$ , where N indicates that the gas volume is calculated at normal pressure and temperature conditions. It is reported that the gasifier can be operated with  $G_H$  in the range 0.1–0.9  $\text{Nm}^3/\text{h cm}^2$ . Normal Imbert

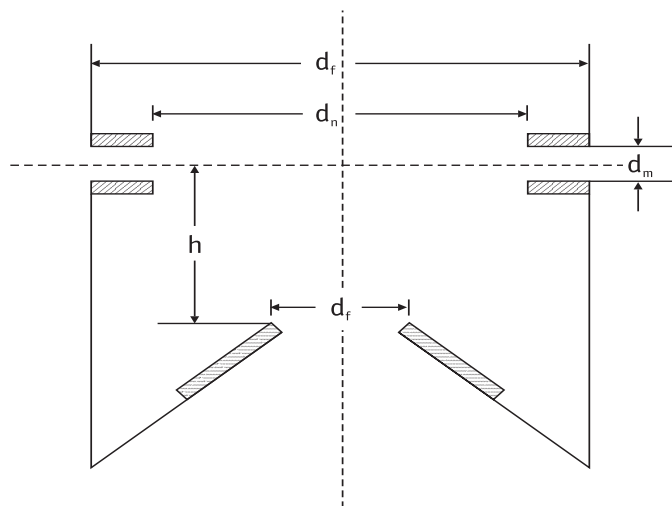


Figure 13.38 Design parameters for Imbert-type gasifiers

**Table 13.12** Typical operational data for different types of gasifiers

Parameter	Downdraft	Updraft	Fluid bed	
			Conventional	Circulating
Grate energy release (GJ/h.m <sup>2</sup> )	1.5–4	2.5–5	6–9	40
Offgas temperature, (°C)	600–800	75–150	650–850	800–900
Oils and tar (kg/kg dry feed)	0.001–0.01	0.05–0.15	0.01–0.05	—
Char loss (kg/kg dry feed)	0.02	0.01–0.02	0.02–0.05	—

**Table 13.13** Producer gas characteristics from different gasifiers

Gasifier reactor type	Gas composition, dry, vol %					HHV MJ/m <sup>3</sup>	Gas quality	
	H <sub>2</sub>	CO	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>		Tars	Dust
Fluid bed air-blown	9	14	20	7	50	5.4	Fair	Poor
Updraft air-blown	11	24	9	3	53	5.5	Poor	Good
Downdraft air-blown	17	21	13	1	48	5.7	Good	Fair
Downdraft oxygen-blown	32	48	15	2	3	10.4	Good	Good
Multi-solid fluid bed	15	47	15	23	0	16.1	Fair	Poor
Twin fluidized bed gasification	31	48	0	21	0	17.4	Fair	Poor

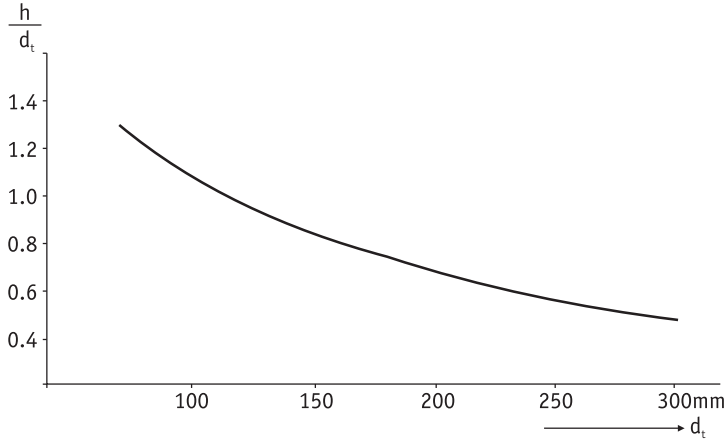
HHV – higher heating value

gasifiers show a minimum value of  $G_H$  in the range 0.30–0.35, resulting in a power turndown ratio of about 2.5–3. With better insulating materials, modern gasifiers can now be operated at lower tar levels with  $G_H$  below 0.15. Based on the maximum value of the hearth load  $G_H$ , the throat diameter  $d_t$  can be calculated. Other dimensions such as the height  $h$  of the nozzle plane above the throat, nozzle area, and the diameter of nozzle top ring (see Figure 13.38 for details) can then be calculated from the graph given by the Swedish Academy of Engineering Sciences reproduced in Figures 13.39 to 13.41 (FAO 1986).

The comparison of various types of gasifiers available during the World War II indicates that the maximum specific gasification rate (or hearth load) is of the order of 0.09, 0.3, and 0.9 Nm<sup>3</sup>/h cm<sup>2</sup> for ‘no throat’, ‘single throat’, and ‘double throat’ gasifiers, respectively (FAO 1986).

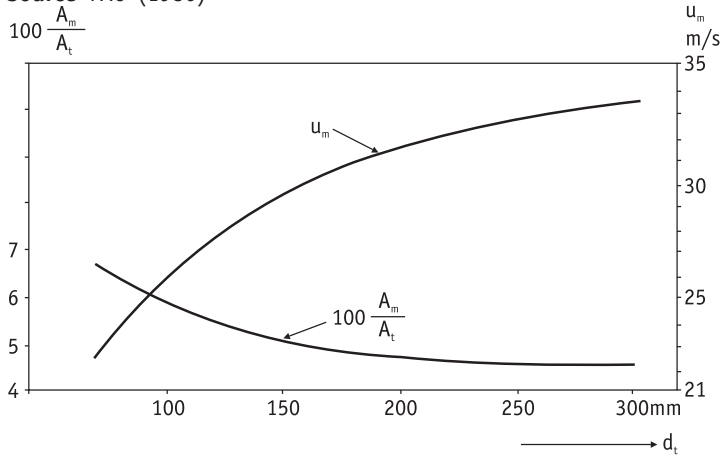
The comparison also shows the following.

- Nozzle air-blast velocities should be of the order of 22–33 m/s.
- Throat inclination should be about 45°–60°.
- Hearth diameter at air inlet should be 10 cm and 20 cm larger than the smallest cross-section (throat) in the case of single- and double-throat design, respectively.



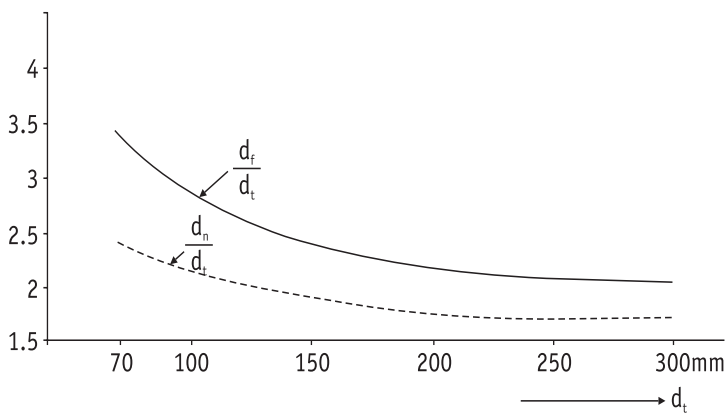
**Figure 13.39** Height of nozzle plane above throat for various throat diameters  
Reproduced with permission from FAO

Source FAO (1986)



**Figure 13.40** Nozzle area for various sizes of gasifier throat  
Reproduced with permission from FAO

Source FAO (1986)



**Figure 13.41** Nozzle ring diameter as a function of throat diameter  
Reproduced with permission from FAO

Source FAO (1986)

- Reduction zone height should be more than 20 cm.
- Air inlet nozzle plane should be located more than 10 cm above the throat section.

It should be emphasized that all these empirical design guidelines are based on the experience with different wood gasifiers.

### Example 3

Design an Imbert-type downdraft gasifier reactor zone for operating a three-cylinder four-stroke engine on 100% producer gas with the following specifications.

Piston diameter (D)	: 110 mm
Piston stroke (s)	: 100 mm
Number of cylinders (n)	: 3
Engine RPM	: 1500
Volumetric efficiency (f)	: 80%

### Solution

For designing a gasifier, the first step is to find out the required gas production rate. Engine swept volume can be calculated as

$$V_s = \frac{1}{2} \times \text{rpm} \times N \times \frac{\pi}{4} \times D^2 \times S$$

$$= \frac{1}{2} \times 1500 \times 3 \times \frac{\pi}{4} \times 0.11^2 \times 0.1 = 2.137 \text{ m}^3 / \text{min} = 128.23 \text{ m}^3 / \text{h}$$

For stoichiometric air-fuel (gas) ratio 1.1:1.0, the air requirement for  $\text{m}^3$  of gas is 1.1. Thus, if  $V_g$  is the gas intake rate, the air + fuel intake will be  $2.1 V_g$ . Hence

$$V_g = f \times \frac{V_s}{2.1} = 0.8 \times \frac{128.23}{2.1} = 48.85 \text{ m}^3 / \text{h}$$

For maximum hearth load  $G_H$  of  $0.9 \text{ N m}^3 / \text{h cm}^2$ , the throat area  $A_t$  is

$$A_t = \frac{V_g}{G_{H\max}} = \frac{48.85}{0.9} = 54.28 \text{ cm}^2$$

Thus, the throat diameter  $d_t$  for circular cross-section works out to be

$$d_t = \sqrt{\frac{4 \times A_t}{\pi}} = \sqrt{\frac{4 \times 54.28}{\pi}} = 8.32 \text{ cm}$$

Height  $h$  of the nozzle plane above the throat cross-section can be determined using the graph in Figure 13.39.  $h/d_t = 1.2$  for throat diameter

$d_t = 83$  mm. Thus,  $h$  works out to be

The diameter of firebox  $d_f$  and the diameter of nozzle top ring  $d_n$  can be determined using the graph in Figure 13.41 by noting the ratio  $d_f/d_t = 3.2$  and  $d_n/d_t = 2.3$ , respectively, for throat diameter  $d_t = 83$  mm. Thus,  $d_f$  and  $d_n$  work out to be

Assuming that five nozzles are used for supplying the required amount of air for gasification and noting the ratio of  $100(A_m/A_t)$  as 6.3 for calculated throat diameter from the graph given in Figure 13.40, the nozzle diameter can be calculated as follows.

The air blast velocity  $u_m$  can also be found from Figure 13.40 as 25 m/s.

### Tar formation and reduction

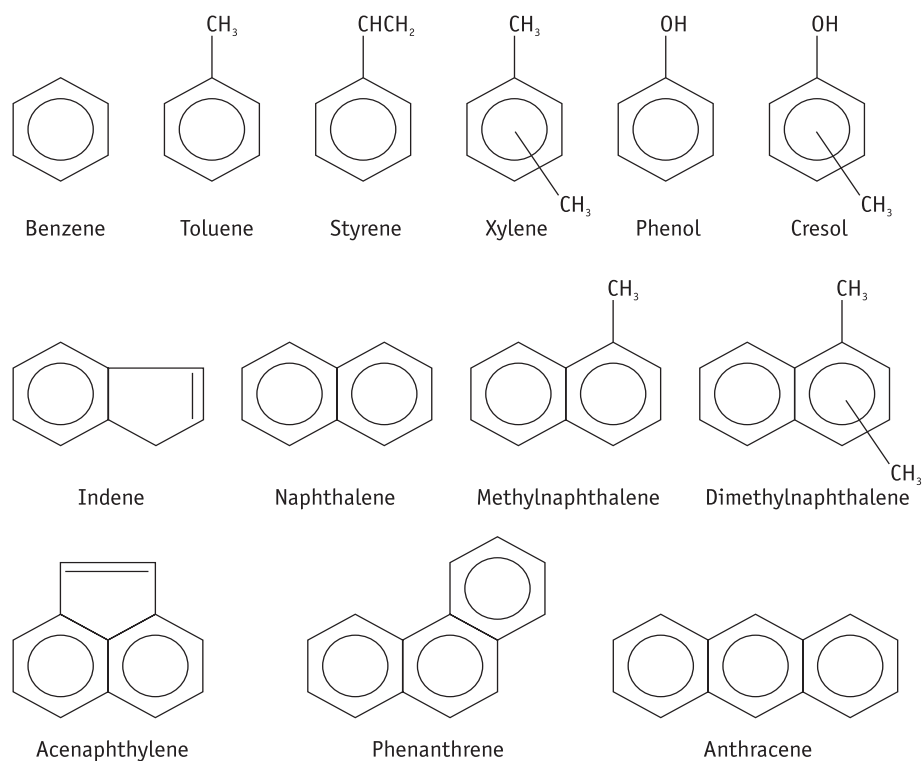
One of the major problem areas in biomass gasification is dealing with the tar formed during the process, namely minimizing its formation and the methods of its reduction or removal once it is formed. Tar is a complex mixture of condensable hydrocarbons and consists of both aromatic and PAHs (poly-aromatic hydrocarbons). The major tar components are toluene, naphthalene, and with process temperatures lower than 800 °C, phenol. Besides these, a number of other compounds occur as trace elements. Figure 13.42 shows the structures of some typical tar components. Macromolecular components with up to seven benzene rings may occur, particularly at temperatures over 800 °C (Spliethoff 2001). In the EU/IEA/US-DoE meeting on tar measurement protocol held in Brussels in 1999, various research groups agreed to define tar as all organic contaminants with a molecular weight

$$\frac{d_f}{d_t} = 3.2$$

Area of

thus no

$$\sqrt{\frac{4 \times A}{\pi}}$$



**Figure 13.42** Structure of various components of tar

greater than that of benzene (Neeft, Knoef, and Onaji 1999). Tar is an undesirable product of the gasification process because of the various problems associated with its condensation, formation of tar aerosols, and polymerization to form more complex structures that cause problems in the process equipment as well as engines used in the application of producer gas.

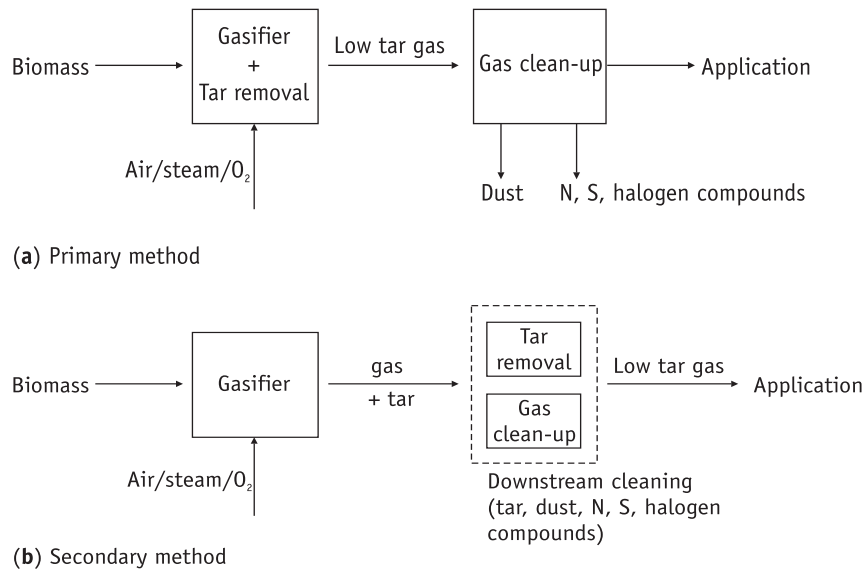
### *Tar removal methods*

Several methods of tar reduction/removal have been reported and can broadly be categorized into two types depending on the location where the tar is reduced.

- In gasifier itself; known as the primary methods
- Outside the gasifier; known as the secondary methods

Figure 13.43 shows the schematic of primary and secondary methods of tar removal. Thus, an ideal primary method concept will eliminate the use of secondary methods.

The following sections describe both methods with emphasis on the primary method.



**Figure 13.43** Tar removal methods

### Primary methods of tar reduction

Primary methods include all measures for reducing tar formation in the gasification process occurring in the gasifier by preventing or converting the tar formed.

### Gasifier operating conditions

The operating conditions play an important role during biomass gasification to obtain good quality gas with regard to its composition and tar content. As discussed earlier, ER of about 0.25–0.3, high uniform fuel bed temperatures (above 800 °C), high superficial velocity, and sufficient residence time can help in achieving a better carbon conversion of biomass and low impurity levels in the producer gas obtained.

Recently, several researchers have investigated pressurized biomass gasification in an effort to achieve higher biomass carbon conversion and lower tar content. Almost complete elimination of phenols was observed at high pressures of the order of 21.4 bars; however, the fraction of PAH was found to increase with higher pressures (Knight 2000). A decrease in the amount of light hydrocarbons (lower than naphthalene) as well as that of tar was observed with an increase in ER for pressurized gasification with almost 100% carbon conversion (Wang, Padban, Ye, *et al.* 1999).

## Bed additives

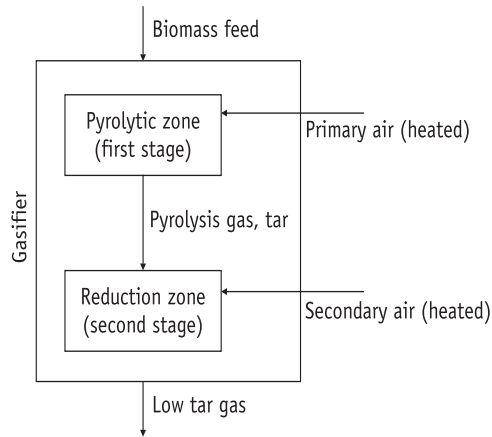
Several catalysts have been tried for tar reduction which include nickel-based catalysts, calcined dolomites, magnesites, zeolites, olivine, and iron catalysts out of which only a few have been tried as active bed additives inside the gasifier. There is a great potential of in-bed additives in terms of tar reduction as they act as in situ catalysts during several gasification reactions. Limestone was one of the first additives used in fluidized bed gasification and steam gasification, and it was found that its use could prevent agglomeration of the bed (Walawender, Ganesan, and Fan 1981). Dolomite is one of the most popular active in-bed additives studied for tar cracking in bed as well as in the secondary reactor (Karlsson, Ekstrom, and Liinaki 1994). Addition of three per cent of calcined dolomite is reported to result in 40% reduction in the tar levels (Narvaez, Orio, and Aznar 1996). Nickel-based catalysts are reported to increase the hydrogen content in the gas with considerable reduction in the methane content. They are also very effective in reducing/decomposing ammonia along with the conversion of light hydrocarbons. However, they have a major problem of fast deactivation due to carbon deposition and poisoning due to the presence of hydrogen sulphide (Wang, Ye, Padban, *et al.* 2000).

## Gasifier design modification

The reactor design is very important for a gasifier system with respect to its efficiency and gas quality (composition and tar content). A two-stage gasifier design has been reported to be very effective in producing clean gas. The basic concept of this design is to separate the pyrolysis zone from the reduction zone. A two-stage gasifier is equivalent to two single-stage gasifiers. Tars formed during the first (pyrolysis) stage are decomposed in the second stage (reduction zone). Figure 13.44 represents the two-stage gasification concepts applied by AIT (Asian Institute of Technology), Bangkok, and TERI, New Delhi, resulting in significant (more than 75%–80%) reduction in tar content in the raw gas (Bhattacharya, Siddique, and Pham 1999; TERI 2005). The successful operation of this gasifier type depends on the stabilization of the pyrolysis zone which, in turn, depends on the balance between downward solid fuel movement and upward flame propagation.

An open-top gasifier design, originally proposed by Tom Reed, has been developed by the IISc (Indian Institute of Science), Bangalore, in which primary air is supplied from the open top of the gasifier and secondary air is supplied through the nozzles in the reduction zone as shown in Figure 13.45. It is claimed that the air supply from the top helps in the upward propagation of

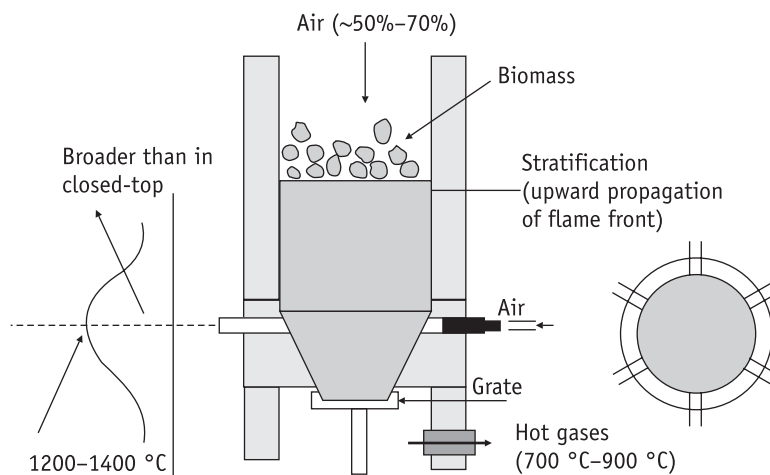




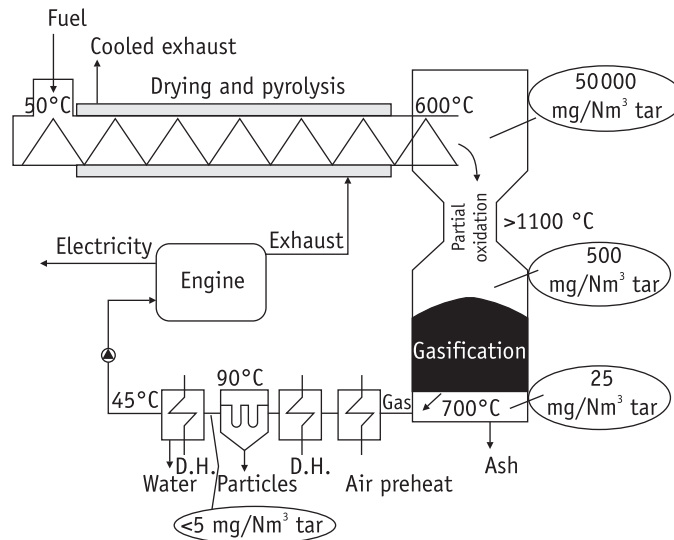
**Figure 13.44** Two-stage gasification principle in TERI gasifier design

reaction front so as to get a higher residence time. It also helps in releasing the volatiles into gaseous form before entering the high-temperature zone where they get cracked to reduce the tar level (Dasappa, Mukunda, Paul, *et al.* 2003).

At DTU (Danish Technical University), another two-stage biomass gasifier design has been developed in which the gasification process occurs in two different systems connected to each other. Pyrolysis of the biomass feed occurs in the horizontal screw-feed pyrolyser, which is externally heated by the engine exhaust and heat recovered from the hot gas followed by partial oxidation of volatile products in the presence of a hot charcoal bed in



**Figure 13.45** Open top gasifier design of IISc, Bangalore  
**Source** Dasappa, Mukunda, Paul, *et al.* (2003)



**Figure 13.46** Two-stage gasification principle of DTU, Denmark  
 Reproduced with permission from Elsevier  
 Source Henriksen and Christensen (1994)

vertical reactor (Figure 13.46) (Henriksen and Christensen 1994). Very low tar ( $<25 \text{ mg/Nm}^3$ ) is reported even in raw gas in this type of gasifier design.

### Secondary methods of tar removal

As mentioned earlier, the quality of gas with regard to impurities such as tar, dust, and water vapour varies with different reactors, and even for a particular reactor type, it varies with the fuel used as well as the operating conditions. Depending on the application, the gas needs to be cleaned and conditioned. There is always a possibility of tar and vapour condensing along with the dust particles to form a semi-solid mixture, which gets deposited and blocks various filters and gasifier system components. In order to prevent this from happening, the gas is cleaned and conditioned. Normally, dust particulates are removed in hot conditions (tar and water vapour remaining in gaseous form) and then the gas is cooled to condense the tar and water vapour to form a liquid condensate, which is then trapped and removed. Further conditioning of gas includes the removal of mist and fine particles ( $<0.1 \mu\text{m}$ ) from the gas. If the gas is to be used for chemical synthesis, it is necessary to remove all unnecessary chemicals such as heavy metals, sulphur, etc., which can poison the catalyst. The extent of treatment required varies, depending on the gas applications.

### For direct combustion

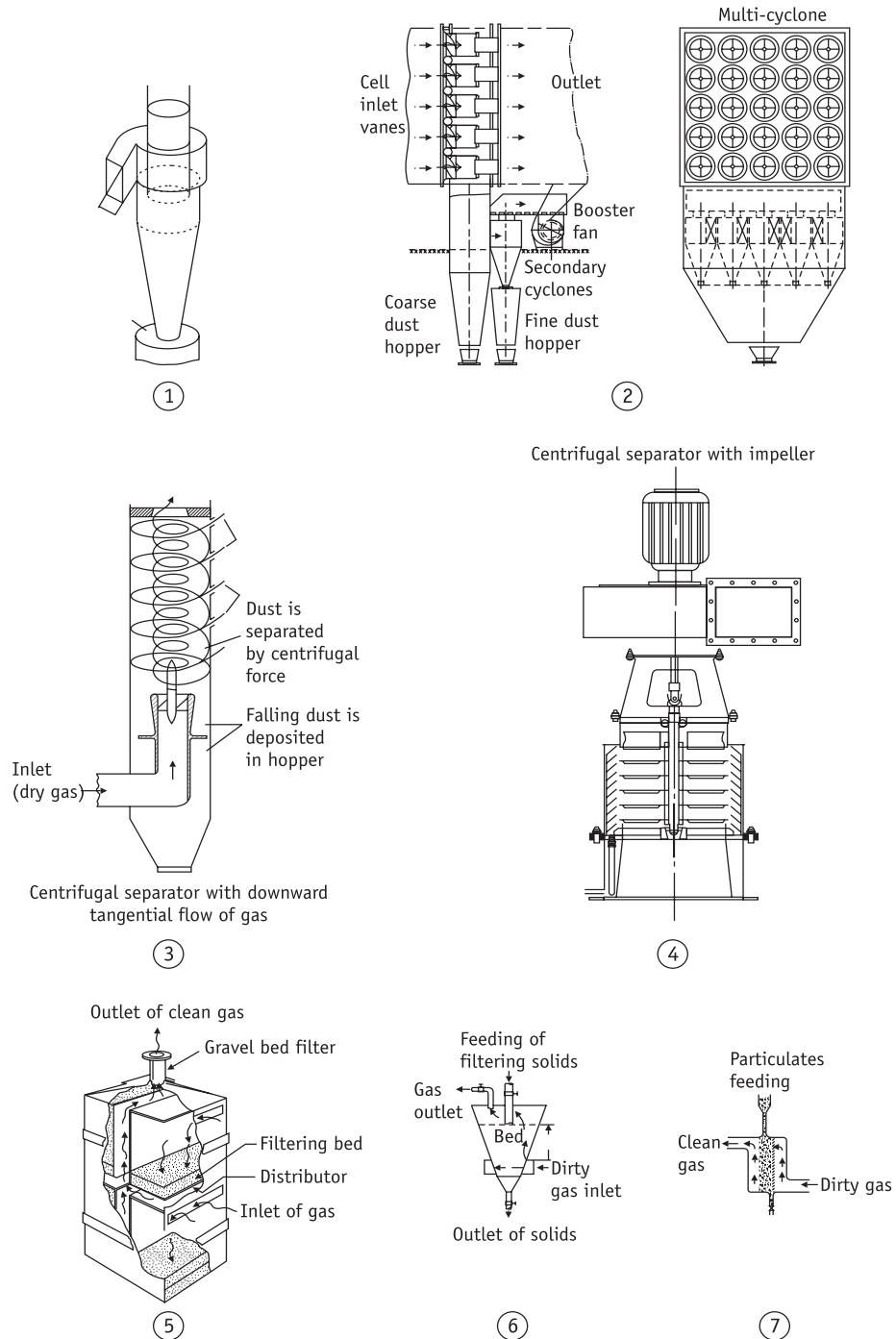
Generally elaborate treatment is not required for direct thermal applications of gas as all the tar gets burned if the burner is designed properly. Thus, only removal of dust particulates is done. However, if the gas is to be used directly for drying seeds or agricultural products, the tar has to be removed, else the seed layer acts like a granular bed filter and tar gets deposited in the first layer (Barrett and Jacko 1984). Similarly, in some cases, the tar has to be removed in pottery or ceramic industry applications to prevent any adverse effect on the product quality. Some earlier applications of gasifiers for tea drying resulted in tainting of tea due to presence of tar.

### For engine or turbine application

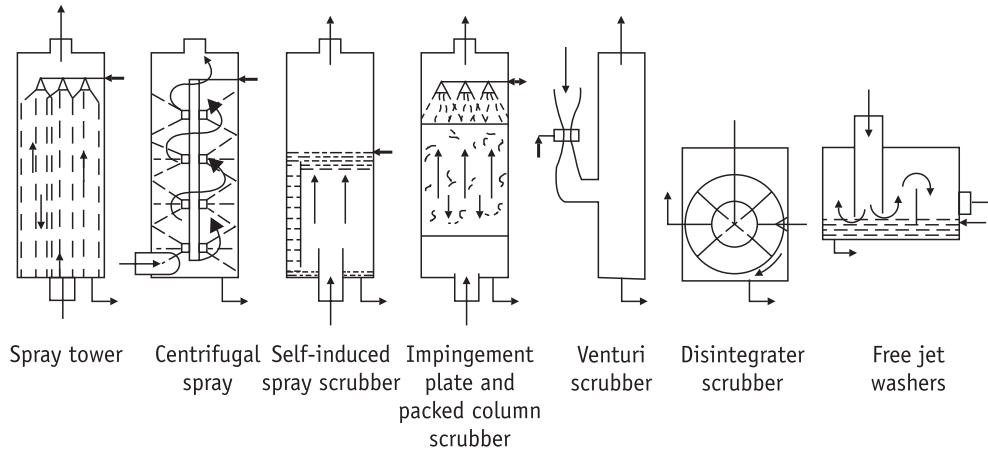
For engine or turbine applications, the gas needs to be cleaned to avoid condensation of the deposit which would cause damage to the mechanical components moving at high speed. There is no consensus about what should be the gas quality limit for tar and particulates. Various manufacturers indicated that the particulate content should be less than 3 mg/Nm<sup>3</sup> for turbines and should lie in the range 50–100 mg/Nm<sup>3</sup> for engines. However, according to the SERI manual (translation of Swedish GENGAS manual), the particulate content ranges between 10 and 20 mg/Nm<sup>3</sup> (Buekens, Bridgewater, Ferrero, *et al.* 1990). Normally, the gas is not allowed to cool down below 80 °C in turbines as below this temperature tar condensation can occur (dew point temperature of producer gas is reported to be about 70 °C). In order to improve the breathing or volumetric efficiency of engine, it is necessary to cool down the gas closer to ambient temperature. Generally, it is observed that for every 10 °C hike in gas temperature, the engine efficiency drops by one per cent.

Various gas treatment techniques used for high temperature particulate removal are as follows (Figure 13.47).

- Cyclones and multi-cyclones (not effective with very small-size particulate distribution, large turndown ratios and if tar droplets are present in the gas)
- Hydraulic dust removal (cleaning fluid must be a liquid)
- Electrostatic precipitator (costly and high power consumption)
- Granular bed (effective if regeneration is not required or easy to organize)
- Porous layer filters (costly but may soon become viable with technological advances in ceramics and polymers)



**Figure 13.47** Various gas treatment techniques for removal of particulates



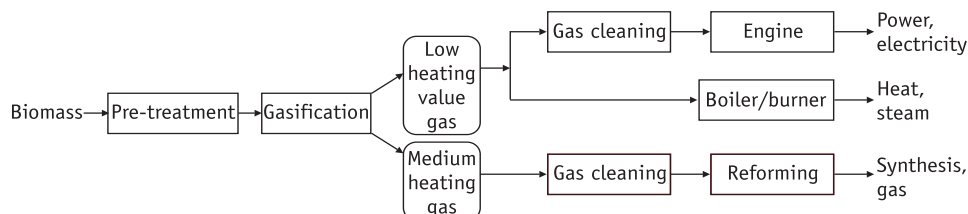
**Figure 13.48** Various wet scrubbers used in gas treatment for tar removal

Various wet scrubbing techniques used for tar condensation and particulate removal are as follows (Figure 13.48).

- Spray towers (very simple, excellent for large particulate removal)
- Centrifugal spray towers (efficiently removes up to  $1\ \mu\text{m}$  particulate)
- Impingement plate and packed-bed column scrubbers
- Disintegrator scrubber (good for submicron particles, high energy requirement:  $5\text{--}7\ \text{kJ}/\text{m}^3$ , requires pre-purification to get concentrations  $<2\text{--}3\ \text{g}/\text{m}^3$  of size  $<10\ \mu\text{m}$ )
- Ejector venturi scrubber (efficient but with a high permanent pressure drop of  $0.4\text{--}1\ \text{kPa}$ , the efficiency improves with higher liquid jet velocity).

### *Producer gas utilization*

Depending upon the gasifying agent, namely, air or oxygen/steam, an LHV (calorific value  $3\text{--}7\ \text{MJ}/\text{Nm}^3$ ) or an MHV (calorific value  $12\text{--}16\ \text{MJ}/\text{Nm}^3$ ) gas is produced. In most of the gasifiers, air is used as gasifying agent and so an LHV gas is produced which needs to be generated and utilized at the site as compressing and transporting it is expensive due to high nitrogen content ( $50\%\text{--}55\%$ ) in the gas. Several possible routes of producer gas utilization are summarized in Figure 13.49. Table 13.14 gives details of biomass pre-treatment, and scale and type of producer gas applications. The MHV gas (obtained from oxygen/steam gasification) can be used to produce chemicals via the synthesis gas (carbon monoxide and hydrogen) after extensive gas cleaning. The units for producing ammonia from biomass gasification tend to be too large to make it economically viable and are not expected to gain attention in near future.



**Figure 13.49** Possible routes for producer gas utilization

## Direct combustion

Various gas characteristics (physical and chemical parameters) and velocity affect the performance of the gas in the burner. These include the following.

- Gas density as compared to air density
- Heating value of gas
- Stoichiometric air requirement (for complete combustion)
- Flame-speed coefficients of gas constituents

A variation in these parameters can result in a flame lift off (excessive gas velocity resulting in the loss of contact with the burner), internal burning of flame back (lower gas velocity than flame propagation resulting in internal burning), or unstable flame. Flame back can be dangerous, as the flame starts moving upstream in a pre-mixed gas–air mixture, leading to explosion. This can be prevented by a flame arrester but can result in extinguishing the flame. While changing the type of gaseous fuel used in a gas burner, there is a need to give attention to the calorific value (heating value), stoichiometric air requirements, and its effect on the adiabatic flame temperature as well as the flue gas volumes. Table 13.15 gives a comparison for the usage of LHV, MHV, and natural gas in the burner.

**Table 13.14** Producer gas (air gasification) applications

Biomass pretreatment			Gasifier reactor	Type of application			Scale of application		
							<100 kWe	100–500 kWe	>1 MW
Simple	Medium	Extensive		Boiler	Burner	Engine			
☐			Downdraft	☐	☐	☐	☐	☐	
	☐		Open core	☐	☐	☐	☐	☐	
☐			Updraft	☐			☐	☐	
	☐		Fluidized bed	☐	☐	☐		☐	☐
		☐	Entrained bed	☐	☐				☐

**Table 13.15** Comparison of heating value, stoichiometric combustion volumes, and flame temperature

Fuel	Stoichiometric combustion volumes (Nm <sup>3</sup> /MJ)				Heating value (MJ/Nm <sup>3</sup> )	Adiabatic flame temperature (°C) (with 10% excess air)
	Air	Fuel	Fuel+air	Flue gases		
LHV	0.20	0.231	0.43	0.39	4.3	1480
MHV	0.20	0.104	0.30	0.27	10.0	1870
Natural gas	0.25	0.027	0.28	0.28	38.0	1860

It can be observed from Table 13.15 that for the generation of 1 MJ, the producer (LHV) gas requirement is 8.5 times higher than the natural gas. As a result, larger amounts of flue gases are generated when producer gas is used instead of natural gas and, therefore, modifications in flue gas paths might become necessary for compensating higher head losses. A lower flame temperature obtained with producer gas can have limitations on its use and at higher temperatures like metal melting or cement kilns, dual firing may be necessary. Recently, some successful attempts have been made to increase the flame temperature by supplying pre-heated air into the gas for high temperature applications like crematoria (Mande, Lata, and Kishore 2001) and steel re-rolling.

## Combustion in an engine

While using producer gas in an engine, combustion limits, knock resistance and compression ratios are important parameters apart from the heating value and the stoichiometric ratio, as discussed earlier. The combustion limits of any fuel-air mixture are the two mixing ratios between which it is possible to ignite the mixture by means of an ignition source (spark in the case of an Otto engine), and the power output depends on the energy content of the fuel-air mixture per unit volume and the average cylinder pressure. The mean effective pressure also depends on the compression ratio and ignition timing. Higher the compression ratio, higher is the thermodynamic cycle efficiency. The compression ratio is normally limited by knowing the tendency of the fuel in the engine under operating conditions. Knocking is an untimely, jerky undesirable combustion process leading to a sharp rise in pressure (up to 50 000 bars/s) and oscillations giving rise to a hammering sound causing mechanical damage to the engine. Continued knocking results in reduced output, overheating, and finally mechanical damage or piston jam/seize. The knocking

tendency is highly influenced by the change in the compression ratio and ignition timing. As a thumb rule, a reduction in the compression ratio by 1 lowers the octane requirement of Otto (spark ignition or SI) engine by 10–15 octanes and increases the start cetane requirement for diesel CI (compression ignition) engine by 3–10 cetane units.

When producer gas is used in an SI engine, the ignition time has to be advanced to gain maximum heating value of slow-burning carbon monoxide (flame speed of 0.52 m/s compared to 2.83 m/s for hydrogen) which, in turn, reduces the mean effective pressure and hence there is a reduction in power output resulting in derating of the engine. Due to the lower compression in the SI engine (about 6–8 as compared to 16–17 in the case of a CI engine), the derating in a SI engine with LHV producer gas is much higher, of the order of 30%–40%, as engine cycle efficiency decreases with lower compression ratio (refer to the section on thermodynamics in Chapter 3). Excessive advancement of ignition timing can at times cause backfiring due to the presence of hot spots. However, producer gas has a lower tendency for knocking due to its LHV and presence of a large fraction of inert nitrogen and carbon dioxide.

Therefore, normally diesel engines are preferred for the use of gas in engine operation as they operate with a higher compression ratio and excess air levels, resulting in lowering of the derating (of the order of 10%). Existing diesel engines can easily be operated on dual fuel (diesel + gas) mode with 15%–30% pilot diesel injection for ignition. Also, it gives the option of an easy switch back to 100% diesel operations and the governor system of diesel injection takes care of fluctuations in operating load conditions (Mande 2005).

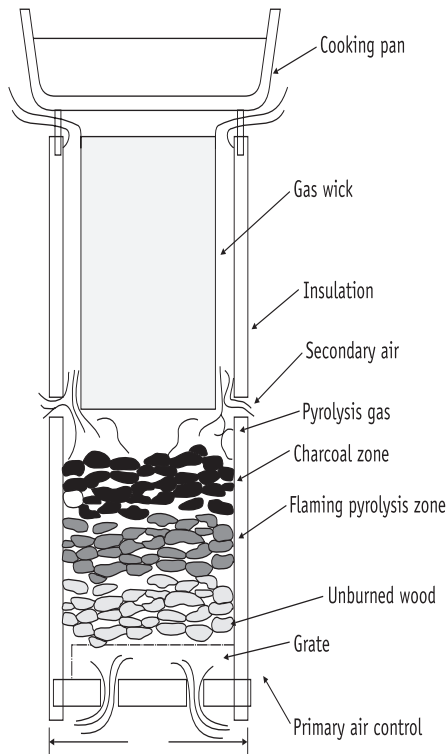
Recently, development of modified diesel engines capable of operating on 100% producer gas has been initiated at several research institutes. The engine modifications basically involve

- modifying piston and/or cylinder head to reduce the compression ratio;
- replacing diesel injectors with spark plugs;
- using a diesel pump governing mechanism for spark distribution; and
- adjusting the spark ignition timing.

### **Inverted downdraft gasifier stove**

Dr T B Reed developed a very small gasifier meant to act on an efficient cook stove, called the IDD (inverted downdraft) natural convection gasifier stove (Figure 13.50). The stove has a high efficiency – of the order of 30%–35%. He later worked on sizing the stove and trying to use it for charcoal making. After much testing and many publications, but with no real success in applications, the work was stopped in 1995. However, later in 1998, Dr Reed began work on



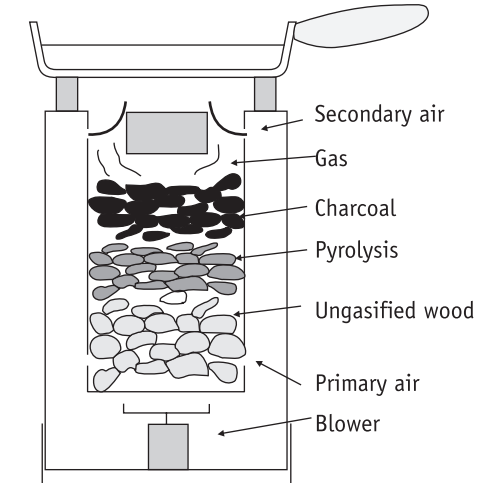


**Figure 13.50** Natural draft gasifier stove operating on inverse down draft principle  
[Reproduced with permission from the Biomass Energy Foundation]

**Source** Reed and Walt (1999)

a smaller, forced convection model with a fan, and in 2001, a prototype forced-air gasifier stove was operated on a kitchen table. Figure 13.51 shows the schematic diagram of gasifier turbo-stove.

A series of modifications and improvisations resulted in the gasifier turbo-stove concept. These modifications included different stackable units in a heat column over a gasifier unit with an air pipe, with smaller holes for the entry of secondary air, pre-heated secondary air, a tapered chimney, and with independent structural components for the stove body. The gasifier chamber was removable and, therefore, could be emptied to save the resultant charcoal, re-loaded with biomass, re-lighted, and re-inserted into the heat column. Later in 2002, the 'Wood Gas Camp Stove' with battery-powered fan and the ability to produce an impressive flame for sustained periods was developed with forced-air designs and with the intention of making a stove for the affluent North American camper market. Variations of these stoves, have been developed and are being disseminated in Sri Lanka and India.



**Figure 3.51** Gasifer turbo-stove  
**Source** Reed and Walt (1999)

## Nomenclature

$A$	Temperature of combustion air
$A_n$	Nozzle area
$A_t$	Throat area
BFB	Bubbling fluidized bed
$C_{pv}$	Specific heat of vessel
$C_{pw}$	Specific heat of water
CI	Compression ignition
CV	Calorific value of fuel
CCT	Controlled cooking test
CFB	Circulating fluidized bed
$D$	Diameter
$D_f$	Firebox diameter
$D_n$	Diameter of nozzle top ring
$D_t$	Throat diameter
$dW$	Amount of water evaporated
EA	Excess air (percentage)
ER	Equivalence ratio
$f$	Volumetric efficiency
$F$	Amount of fuel burnt
$G_H$	Hearth load