High temperature syngas coolers

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

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Abstract

The temperature of synthesis gas (syngas) leaving a gasifier could be as high as 1600°C, depending on the gasification process employed. Recovery of heat from the high temperature syngas is essential for attaining high process efficiency. Heat recovery systems can reclaim a significant portion (5–25%) of the energy in the feed, depending upon the technology used. It is estimated that compared to a gasification plant without hot syngas heat recovery, the use of a heat recovery system can increase the process efficiency by approximately 5 percentage points. High temperature syngas can be cooled using a radiant, a convective, a direct quench cooler or any combination of these coolers. The selection and actual design of a syngas cooling system are influenced by factors such as the type of gasifier used, the characteristics of the coal feed, the overall gasification process application and costs. Various high temperature syngas cooling systems based on mature technologies have been developed to meet varying technological challenges and process requirements. This report reviews all types of commercial high temperature syngas cooling and heat recovery systems. The design concepts and operating experience of the syngas cooling systems in commercial scale IGCC plants are examined and discussed.

Acronyms and abbreviations

BFW	boiler feed water
CCS	carbon capture and storage
CCT	clean coal technology
CSC	convective syngas coolers
HGCU	hot gas cleaning unit
HP	high pressure
HRSG	heat recovery steam generator
HTW	High Temperature Winkler
IGCC	integrated gasification combined cycle
IP	intermediate pressure
KBR	Kellogg, Brown, & Root
RGHE	raw gas heat exchanger
R&D	research and development
RSC	radiant syngas cooler
SCGP	Shell Coal Gasification Process
SES	Synthesis Energy Systems, Inc.
SFG	Siemens Fuel Gasifier
syngas	synthesis gas
TRIG	transport integrated gasifier
ZZ	Zao Zhuang

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1 Introduction

Gasification is used to convert solid, liquid or gaseous hydrocarbon feedstock such as coal, heavy oil, petroleum coke (petcoke) and biomass into a high grade synthesis gas (syngas) through chemical reactions of the feedstock with oxygen-steam mixtures. The syngas produced can be used as chemical feedstock for the production of hydrogen, ammonia and other chemicals, or as fuel for power generation. Integrated gasification combined cycle (IGCC) is an advanced power generation system that can potentially achieve high energy efficiencies and low pollutant emissions.

With the exception of natural gas feeds, the hot syngas generated in a gasifier is contaminated with various components including particulates, sulphur and chlorine compounds. These contaminants must be removed before the syngas is used, whether as chemical feedstock or as fuel. The gas cleaning processes usually operate at temperatures considerably lower than that of the gasifier. As a result, the syngas needs to be cooled to a required temperature before entering the downstream gas cleaning units. This cooling task is performed by the syngas cooler.

The temperature of syngas leaving a gasifier can be as high as 1600°C, depending on the gasification process used. Recovery of heat from the high temperature syngas is essential for attaining high process efficiency. Heat recovery systems can reclaim a significant portion (5–25%) of the energy in the feed, depending on the technology used. It is estimated that compared to a gasification plant without hot syngas heat recovery (for instance, with direct water quenching), the use of a heat recovery system can increase the process efficiency by approximately 5 percentage points (Alstom, 2015). A syngas cooling and heat recovery system acts as a heat exchanger/steam generator, receiving the hot raw syngas from the gasifier and cooling it by transferring the heat to the cooling medium (water) to generate steam. The steam produced can be utilised for process purposes or to generate electric power.

The syngas cooler is one of the most crucial and highly loaded components in the gasification plants. It operates with gas inlet temperatures ranging from 1600°C to 400°C and gas-side pressures up to 8 MPa. The high operating parameters combined with harsh operating conditions, such as corrosive raw gas components (H_2S, HCl, H_2) and high dust loads, impose challenging requirements on the design and material selection. This report reviews all types of commercial high temperature syngas cooling and heat recovery systems. It begins with a brief introduction to the types of commercial gasification processes in Chapter 2. The types of syngas cooler, the arrangement and design of syngas cooling and heat recovery system are discussed and compared in detail in Chapter 3. The commercial high temperature syngas cooling systems developed for IGCC plants are described in detail in Chapter 4, and the operating experiences of these systems are discussed in Chapter 5. Finally, conclusions are drawn in Chapter 6.

The selection and actual design of a syngas cooling system are influenced by factors such as the type of gasifier employed, the characteristics of the coal feed, the overall gasification process application and costs. Over the past three decades, various high temperature syngas cooling system designs based on mature design concepts have been developed to meet varying technological challenges and process requirements. Operating experiences of commercial gasification plants, especially of the coal-based commercial scale IGCC demonstration plants are now available providing valuable knowledge for improving and optimising the designs and operating conditions of future more efficient, more reliable syngas cooling and heat recovery systems.

2 Overview of gasification processes

Gasifiers (gasification reactors) are currently in use in different industrial processes such as chemical, petrochemical plants and utilities. Different types of gasifiers have been designed and developed in order to fulfil the specific requirements of one and each of these processes and for different types of fuel. Despite the various types of gasifiers, differing in design and operational characteristics, there are three main gasifier categories of the commercially available gasifiers, namely moving bed gasifiers (also referred to as fixed bed gasifiers), fluidised bed gasifiers and entrained flow gasifiers.

2.1 Moving bed gasifiers

Moving bed gasifiers can be divided into two different categories: counter-current (up-draught), and concurrent (down-draught) gasifiers. The configurations of counter-current and concurrent moving bed gasifiers are similar in design, differing mainly on the location of oxidant input and syngas output.

In a counter-current gasifier, feedstock such as coal and biomass is fed into the top of the gasifier and moves downward through the bed, while reacting with oxygen and steam that is introduced at the bottom of the gasifier and flows upward in the gasifier. The syngas product exits from the top of the gasifier as shown in Figure 1. Reactions within the gasifier occur in different zones. In the drying zone at the top of the gasifier, the entering coal is heated and dried, while cooling the product gas before it leaves the reactor. The coal is further heated and devolatilised by the higher temperature gas as it descends through the devolatilisation zone where gaseous products rich in hydrocarbons and char are formed. In the next zone (the gasification zone), the char is gasified by reacting with steam and carbon dioxide. In the combustion zone at the bottom of the gasifier where the highest temperature is attained, oxygen reacts with the remaining char. The oxidation reactions produce the heat required for the endothermic gasification reactions.

In a concurrent gasifier, coal is fed at the top of the reactor while the oxidant enters near the middle section. The ash accumulates at the bottom of the gasifier while syngas flows out of the bottom directly before the ash removal. In a counter-current gasifier, the oxygen, and possibly steam, is fed at the bottom while coal is fed at the top of the reactor. The main difference between concurrent and counter-current gasification is how the gasification zones are organised within the reactor. In concurrent designs, oxidation occurs in the middle of the reactor and reduction reactions take place at the bottom.

Ash can be rejected either as a solid or as a liquid slag. In the dry-ash mode of operation, the temperature is moderated to below the ash melting temperature by reaction of the char with excess steam. The ash below the combustion zone is cooled by the entering steam and oxidant (oxygen or air) and produced as a solid ash. In the slagging version, much less steam is used, and as a result, a much higher temperature is achieved in the combustion zone, melting the ash and producing slag.

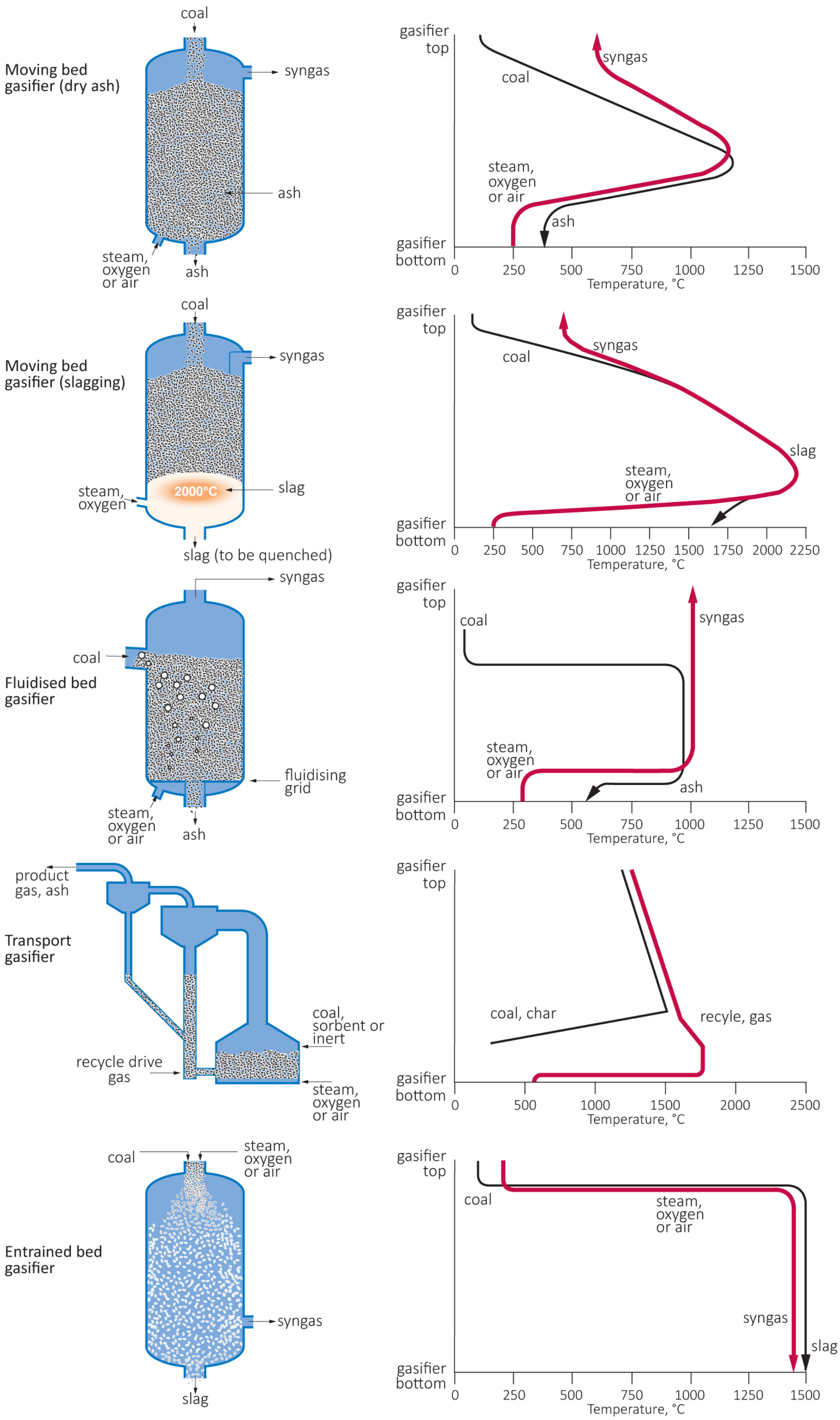

Figure 1 Main types of gasifiers

There is a significant temperature gradient within the bed (*see* Figure 1). The maximum temperatures in the combustion zone at the bottom of the reactor are typically in the range of 1500–1800°C for slagging gasifiers and around 1300°C for dry ash gasifiers. As the flow is counter-current, the gas leaving the gasifier is cooled by the incoming feed and the gas exit temperature is typically 400–600°C. The moisture content of the feed coal is the main factor which determines the discharge gas temperature. High moisture lignite coals result in lower temperatures than low moisture bituminous coals.

As the raw gas traverses through the devolatilisation and drying zone, it contains a significant amount of tars, phenols, oils and low boiling point hydrocarbons that have been produced in the devolatilisation zone and are carried upwards by the gas before reaching the gasification zone. The temperatures in the upper section of the gasifier are not sufficiently high for tars, phenols and other hydrocarbons to decompose. Methane formation is also very high. As a result, the produced syngas has a high heating value. The carbon conversion rate in the reactor is very high whilst the consumption of oxygen is low. The counter-current flow and inherent recuperation of the sensible energy in the gas through devolatilisation and drying of coal result in a high thermal efficiency of the gasification process and give these gasifiers higher cold gas efficiency (80–90%) compared to other types of gasifiers. Table 1 compares some of the characteristics of the different types of gasifiers. Typical examples of moving bed gasifiers include Lurgi dry ash gasifiers and the British Gas/Lurgi (BGL) slagging gasifiers.

Table 1 Comparison of gasifiers (modified from Cortés and others, 2009)

	Moving bed		Fluidised bed		Entrained flow
Operating temperature (°C)	300–1800		650–1100		1500–1900
Operating pressure (MPa)	1–10		1–4		2.5–8
Syngas	contains tar, oil, phenols, ammonia and small amounts of particulate		low tars and phenols; uniform composition; high content of ash and char		no tars, or phenols but ash and char
Syngas temperature (°C)	400–600		700–900		900–1600
Residence time (s)	900–3600		5–100		1–10
Ash condition	dry	slagging	dry	agglomerating	slagging
Coal rank	low	high	low	**any**	**any**
Oxidant requirement	low	low	moderate	moderate	high
Steam requirement	high	low	moderate	moderate	low

The tars and other higher molecular weight hydrocarbons contained in the syngas tend to condense and foul the heating surface upon cooling. Also, due to the relatively low temperature of the exit syngas, this type of gasifier does not have high temperature heat exchangers. Typically, the raw gas leaving the gasifier is quenched by direct contact with recycle water to condense and remove tars and oils. After quench, heat may be recovered from the gas by generation of low pressure steam. Therefore, the cooling systems adopted in moving bed gasification processes will not be discussed in this report.

2.2 Fluidised bed gasifiers

In a fluidised bed gasifier, a mixture of gasification agent (usually air, but oxygen is also used) and steam passes through a bed of fuel particles at a high enough velocity to suspend the solids so the resulting bed within the gasifier acts as a fluid. These gasifiers employ back-mixing, and efficiently mix feed coal particles with coal particles already undergoing gasification. Coal enters at the side of the reactor into the hot fluidised bed and mixes rapidly with the bed material and almost instantaneously attains the gasification temperature. This leads to higher throughputs in fluidised beds, as compared with moving bed gasifiers. Due to the thorough mixing within the gasifier, a uniform temperature distribution is obtained in the reactor bed (*see* Figure 1). Lime, limestone or dolomite can be added for in-bed sulphur removal. The gasifiers normally operate at moderately high temperatures (900–1100°C) to achieve an acceptable carbon conversion rate (90–95%) and to decompose most of the tar, oils, phenols, and other liquid by-products. However, the operating temperatures are usually lower than the ash fusion temperature so as to avoid clinker formation and the possibility of de-fluidisation of the bed.

Some char particles are entrained in the raw syngas as it leaves the top of the gasifier, but are recovered and recycled back to the reactor via a cyclone. Ash is removed below the bed and heat is recovered from the ash by heating the incoming steam and recycle gas. The temperature of syngas exiting a fluidised bed reactor is usually in the range of 800–1000°C. It is free of tars and with low fly ash content. The cold gas efficiency is approximately 80%.

Fluidised bed gasifiers may differ in ash conditions (dry or agglomerated) and in design configurations. Also, depending on the degree of fluidisation and bed height, these types of reactors are sometimes classified into: bubbling fluidised bed gasifier, circulating fluidised bed gasifier and transport gasifier.

2.2.1 Bubbling fluidised bed gasifier

Gasifying agent is fed under the bed and this ascendant flow with a relatively low velocity creates bubbles while traversing the bed. Fuel is fed into or above the bed. There is a freeboard above the bubbling bed where the gas-phase reactions take place. A cyclone at the exit of the gasifier removes the fly ash from the syngas. The operating temperature of bubbling bed gasifiers is typically in the range of 650–950°C.

2.2.2 Circulating fluidised bed gasifier

The velocity of gasifying agent is higher than that in the bubbling bed gasifiers, to suspend the fuel particles throughout the reactor. A cyclone separates the particles and recycles them back into the bed. The operating temperature of circulating bed gasifiers is typically in the range of 800–1000°C.

2.2.3 Transport gasifier

This type of gasifier is between fluidised bed and entrained flow gasifiers. It operates at higher velocities, riser densities and solids circulation rates than most conventional circulating fluidised bed reactors, leading to better mixing and higher heat and mass transfer rates. A transport gasifier consists of a mixing zone, riser, disengager, cyclone, standpipe, loopseal, and J-leg (*see* Figure 1). The mixing section has a combustion zone and a coal devolatilisation zone. Coal is fed slightly above the mixing zone in a reducing atmosphere and is heated rapidly by the circulating solids and combustion gases in a devolatilisation zone. Limestone is usually added as sulphur sorbent. The combustion zone is fed with recycled char, ash and sorbent and mixed with the oxidant and steam. The endothermic coal gasification reactions take place primarily in the riser above the coal feed injection point (gasification zone). Heat for the coal devolatilisation and gasification reactions is provided by char combustion in the combustion zone. Unlike conventional fluidised bed gasifiers that have a uniform temperature distribution within the bed, there is a temperature gradient within transport gasifiers as shown in Figure 1.

Additional residence time in the riser section allows the char gasification, methane/steam reforming, water gas shift and sulphur capture reactions to occur. The char along with recirculating ash is separated from the syngas in a cyclone and recycled back to the gasifier via a standpipe and J-leg. The raw gas from the cyclone is sent to a syngas cooler. The operating temperature of transport gasifiers is between 815-1065°C.

Examples of fluidised bed gasifiers include U-gas gasifier, High Temperature Winkler (HTW) gasifier and Kellogg, Brown, & Root (KBR) transport integrated gasifier (TRIG).

2.3 Entrained flow gasifiers

Entrained flow gasifiers are characterised by higher velocities and higher temperatures than moving or fluidised bed gasifiers. They operate at temperatures between 1200°C and 1600°C and pressures range from 2–8 MPa with most large plants operating at around 2.5 MPa. In an entrained flow gasifier, coal and oxidant (air or oxygen) and steam are fed concurrently into the gasifier at high velocities and move either in an up-flow or a down-flow direction. This results in the oxidant and steam surrounding or entraining the coal particles as they traverse the gasifier in a dense cloud and extremely turbulent flow, which lead to a uniform temperature distribution within the gasifier vessel ensuring rapid carbon conversion (*see* Figure 1). Due to the high velocities, the residence time in these gasifiers is short, typically in the order of a few seconds. High carbon conversion (98–99.5%) at these conditions is achieved by using finely ground coal and high gasification temperatures. The syngas leaves the reactor typically at high temperatures of 1260°C and higher. Given the high operating temperatures, gasifiers of this type melt the coal ash into vitreous inert slag.

The fine coal feed can be fed into the gasifier in either a dry or slurry form. The slurry feed introduces water into the reactor that needs to be evaporated. The result of this additional water is a product syngas with higher H_2 to CO ratio, but with a lower gasifier thermal efficiency. The cold gas efficiency is approximately 80%.

Entrained flow gasifiers are the most versatile type of gasifiers in that they can gasify practically all types of coal regardless of coal rank, caking characteristics or amount of fines, though feedstocks with lower ash contents are preferred. Other advantages include high-load capacity, high carbon conversion, and a product gas rich in CO, CO_2, H_2, H_2O and free of tars and phenols. On the other hand, high gasification temperatures raise a number of challenges: burner and gasifier reliability due to corrosive and sticky slag, and the requirement to cool extremely hot syngas. Oxygen consumption in entrained bed gasifiers is typically the highest among the gasifier types.

Currently, there are several variations of entrained flow gasifiers, such as the GE Energy gasifier, Shell gasifier and MHI gasifier, available in today's market. For interested readers, detailed descriptions and technical reviews of gasification processes and individual commercial gasifiers are available elsewhere (Breault, 2010; H2-IGCC Project, 2010; Cortés and others, 2009; Fernando, 2008).

3 High temperature syngas cooling systems

Syngas leaves a gasifier at high temperatures varying from around 500°C to 1600°C. The raw syngas is contaminated with various components such as particulate, sulphur and chlorine compounds or tars which must be removed before the syngas can be used. Gas cleaning processes usually operate at temperatures considerably lower than that of the gasifier itself, and therefore, there is always the necessity to cool the syngas. The hot syngas can be cooled by a radiant and/or convective heat exchanger and/or by a direct quench system. In most cases, it is desirable to recover and make good use of the sensible heat in the gas, for example, by raising steam for in-plant power generation or process heating. On the other hand, the characteristics of the various gasification processes and the diversity in the properties of syngas produced raise considerably different syngas cooling tasks. Consequently, several syngas cooling systems using various types of coolers with different equipment designs have been developed.

3.1 Radiant syngas cooler

The sensible heat in high temperature raw syngas (>700-1650°C) can be recovered by a radiant type heat exchanger (heat recovery boiler). Radiant syngas coolers (RSC) use radiant heat transfer to cool the hot syngas. The radiant heat exchanger tube arrangement bears some resemblance to cylindrical fired heaters where cage shaped tube panels are used. Figure 2 illustrates a radiant screen cooler. Hot gas flows up or down in the radiant cooler, depending upon gasifier design, giving heat to the water that flows in tubes built into the heat transfer surface. High pressure (HP) steam is generated. The molten slag drops into a slag quench chamber at the bottom of the radiant syngas cooler where it is cooled and removed for disposal.

Figure 2 A radiant screen cooler by Alstom (Alstom, 2015)

In general, division walls (or platens) with water tubes built inside are placed inside the RSC. These division walls increase the heat transfer surface area and therefore enhance radiant heat transfer from the gas and entrained particles. The division walls, acting as radial platens, are arranged like the spokes of a wheel, where such radial platens are uniformly spaced at equal intervals. Figure 3 shows the inside of a

RSC with high alloy heat recovery walls. There are variations in RSC designs. The basic structure of a RSC with double water-cooled cage-walls is illustrated in Figure 4. The RSC is a cylindrical enclosure constructed with water cooled tubes and membrane, known as the 'cage-wall'. There are several division walls inside the inner cage-wall. In all these designs, the platens are confined to an annular region of the furnace plan area within the RSC. The centre of the furnace is open to allow large slag particles to fall through the RSC without excessive deposition on the platens.

Figure 3 Inside of a RSC with division walls (Alstom, 2015)

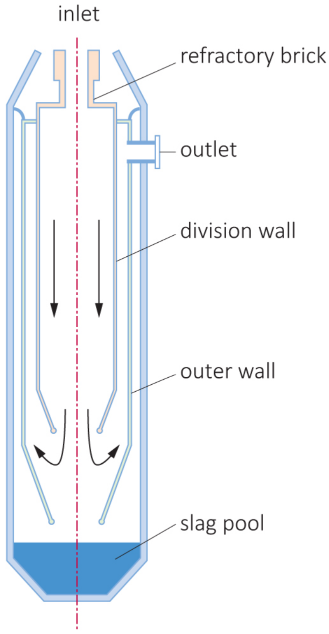

Figure 4 Structure of a RSC (Ni and others, 2009)

As in direct combustion, a radiant heat exchanger is only used for very high temperature operation. It can be prone to fouling and rappers or blowers can be used for cleaning.

It is necessary to distinguish between radiant syngas coolers and radiant coolers used in gasifier reactors. Some gasifiers, such as those developed by Shell and Siemens, use a membrane wall inside the reactor vessel covered with a relatively thin layer of refractory. The membrane wall consists of high-pressure tubes in which water is circulated and evaporated, generating high-pressure steam. Molten slag in contact with the cooling surface is cooled and solidified, forming a layer of coating on the surface. The solid slag layer and refractory provide enough insulation between the cooled membrane wall and reacting gasifier flows to enable molten slag to contact, wet, and run down the wall and be collected at the bottom of the gasifier. Therefore, the liquid slag does not come into contact with the wall avoiding corrosion and erosion problems. It should be noted that the built-in membrane wall is used for the purpose of cooling and so to extend the life expectancy of the refractory. Heat recovery by steam generation is generally not a major objective.

3.2 Convective syngas cooler

Convective syngas coolers (CSC) are usually shell and tube type heat exchangers/boilers consisting of a set of tubes in a container. Convective coolers are generally used to recover heat from coal-derived syngas with temperatures of 1000°C or lower, depending on the characteristics of coal feed. The heat is transferred by convection and conduction. High and/or intermediate pressure (IP) steam is generated by CSC. Both fire tube boiler and water tube boiler designs have been used for CSC. In fire tube boiler designs, the hot raw syngas flows inside the tubes, while high pressure steam is generated on the outside. This means that the tubes are subjected to an external pressure because the steam pressure is greater than the gas pressure in practically all applications. Depending on the design, maximum steam pressure is between 10 and 15 MPa. An advantage of fire tube boilers is the well-defined gas flow in the tubes.

The maximum material stresses occur at the gas inlet nozzles and therefore the boiler gas inlets need to be designed carefully in order to cool the gas inlet zone and to ensure the dust-laden syngas does not cause erosion. Borsig Process Heat Exchanger GmbH (Germany, http://phe.borsig.de/) has developed a fire tube boiler design for CSC. In this design, a conical inlet section is used to reduce the turbulence at the inlets. The gas inlet nozzles are designed with reinforcement ribs on the waterside and ceramic coating on the gas side, as shown in Figure 5. The gas inlet nozzles are cooled by forced and natural circulation. Boiler water is taken from the lower boiler area and supplied to the double tubes in the gas inlet zone by recirculating pumps. The application of reinforcement ribs on the waterside allows reduction of the wall thickness and thereby the wall temperatures in this area. The application of a ceramic protection coating on the gas side of the inlet nozzles considerably improves the resistance to corrosion and erosion. The coating also reduces the wall temperatures due to its low conductivity. The tubes are designed as helical wound heating surfaces. The tube diameter decreases in several steps (usually four to five steps) to maintain a minimum gas velocity in the range of 25 to 35 m/s. This ensures a self-cleaning effect which is necessary due to the high particulate burden of the gas. The developer claims that this boiler design is suitable for all gasification processes. However, it has been used mainly for the GE Process (as discussed in Section 4.1.1).

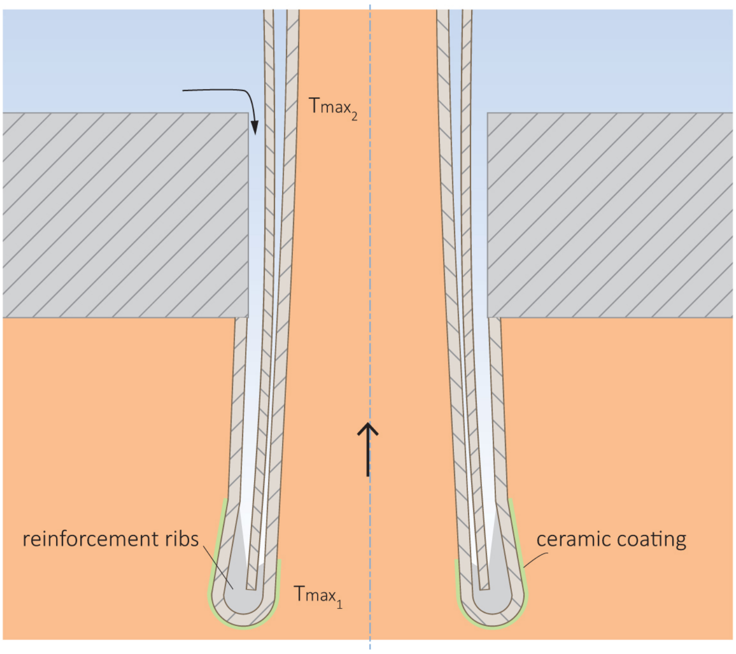

Figure 5 Forced cooling of the gas inlet nozzles

Unlike fire tube boilers, water tube boilers pass water through the tubes, which is then heated externally by hot syngas. The heated water rises into a steam drum, where it can be reheated by a superheater to achieve even higher steam temperatures. With water tube boilers, the local flow pattern around the tubes is less even than with a fire tube boiler, and there can be areas of almost stagnant gas and hence the risk of dust accumulation in the boiler. Water tube boilers can handle higher operating pressures (up to 34 MPa) and provide greater steam output than fire tube boilers. They are commonly used in power generation plants that require large amounts of high pressure steam production. Because there is less water volume, a water tube boiler can handle steam fluctuations more precisely than a fire tube boiler and has generally better turndown. However, the fire tube configuration is often selected for CSC if there is a high particulate content in the syngas. The high syngas velocity inside tubes can minimise the dust deposition and hence prevent plugging of the cooler. Water tube boilers are higher in cost than fire tube boilers. Figure 6 shows the tube arrangement used in a fire tube and a water tube convective heat exchanger. Various tube arrangements such as double tube, spiral and helically coiled designs have been developed and applied in convective heat exchangers.

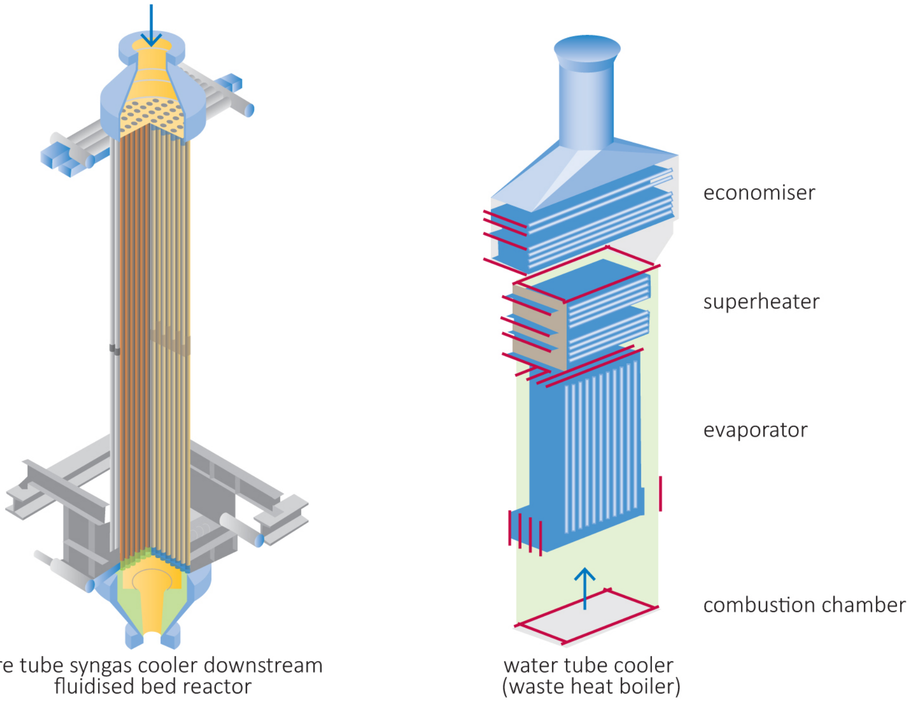

Figure 6 Tube structure inside a fire tube and a water tube convective heat exchanger (Alstom, 2015)

Depending on the type of gasification process the syngas downstream of the steam generator may be further cooled by a steam superheater (special SCS design) and economisers.

3.3 Direct quenching

Quenching is a rapid cooling process. Quenching can be direct or indirect. Indirect quenching is often used for the generation of high-pressure steam by specially designed heat exchangers such as radiant coolers described above. With indirect quenching, there is no direct contact between hot syngas and quenching medium. With direct quenching, the hot raw syngas is rapidly cooled by injection of cooling medium into the syngas. Direct quenching can be very efficient and high cooling rates can be achieved. There are several different direct quenching techniques such as water quench, gas quench and chemical quench.

3.3.1 Water quench

A water quench uses the sensible heat of the syngas to vaporise the injected water. The quench may be a partial quench or a full (total) quench. In partial quench, only just enough water is evaporated to cool the syngas to a desired temperature (for instance, 900°C). In full quench, sufficient water is evaporated to saturate the syngas with water vapour. With a partial quench, heat recovery using convective heat exchangers could be integrated to produce high-pressure steam, whilst with a full quench, no high-pressure steam is generated since there is no heat recovery. In both cases, the addition of water drives the water gas shift reaction to increase the H_2/CO ratio.

3.3.2 Gas quench

One example of the use of a gas quench is in the Shell gasifier, where the hot (1500°C) raw syngas exiting the gasifier is quenched to 900°C by a stream of recycled, cooled, ash-free syngas. The quenched syngas is then further cooled in a CSC. This way, the heat is used within an unproblematic temperature range. When a gas quench is used, all the sensible heat in the gas leaving the gasifier is used for raising additional steam, which results in high efficiencies of IGCC power plants.

3.3.1 Chemical quench

The quench process in which the quenching medium undergoes chemical reactions may be referred to as chemical quench. There is less experience with chemical quench as this is a concept not widespread in industry. In principle, the syngas or any other hot process stream may be quenched at the same time as the thermal energy is used to produce other valuable products. This may give a more effective heat utilisation than the production of steam. When chemical quench is applied to coal gasification, the gasification process is divided into two stages. The first stage gasifier operates under slagging conditions using relatively high oxygen/steam ratios to produce high temperature syngas. The sensible heat in the hot syngas leaving the first gasification stage is used to gasify a second-stage feed. The coal gasification by CO_2 and H_2O in the second stage is an endothermic reaction, and the heat absorbed is sufficient to cool the syngas to temperatures under which the ash formed in the second stage gasification is dry. With chemical quench, the sensible heat of the hot syngas is converted into chemical energy of the gas produced (CO and H_2).

Chemical quenching is advantageous because the temperature of the syngas exiting the gasifier is lowered and thus has less sensible heat, leading to increased cold gas efficiency. Liu and others (2010) compared the exergy loss of high temperature syngas after quench cooled from 1227°C to 1027°C (1500 to 1300 K) using different quenching techniques. They found that water quench led to the biggest exergy loss of 7.4%. The exergy loss after gas quench was 2.3%, one third that of water quench, whilst the exergy loss due to chemical quench was negligible (0.37%). Chemical quench can be applied in combination with other heat recovery systems for steam production to achieve increased total process efficiency. A disadvantage is that some tars may form, making the downstream syngas cleaning more complex.

3.4 Syngas cooling system designs

The selection and design of a syngas cooling and heat recovery system have to consider the characteristics of the coal feed and syngas produced, the type of gasifier used, and the overall gasification process application. The temperature of the cooled syngas is determined by the gas cleaning process immediately downstream of the syngas cooler. Two aspects of gas cleaning need to be carefully considered in designing the cooling system. These are particulate removal and condensation — whether condensation of tars, ammonium chloride or simply water. The first cleaning stage after the syngas cooler comprises the removal of any solids present in the syngas. Effective solids removal is possible at temperature below 500°C, whereas for the removal of acid gases and other contaminants (usually using wet scrubbers) the syngas has to be further cooled to essentially ambient temperatures.

The cost of a syngas cooler is also an important factor influencing the syngas cooling system design as it can be a significant portion of total capital cost of the gasification plant. Various syngas cooling systems are in operation in existing IGCC plants.

3.4.1 Radiant and convective cooling

It is common that a syngas cooling system combines different types of syngas coolers. Uebel and others (2014) identified six design concepts of syngas cooling systems (*see* Figure 7) that could be adopted by Siemens entrained flow gasifiers. One or more of these cooling system designs may be integrated into other types of gasifiers. The radiant and convective syngas cooling design is suitable for cooling hot syngas with a temperature substantially higher than 900°C. The hot syngas from the gasifier enters a RSC in which it is cooled to a temperature of approximately 800°C while high-pressure steam is generated. The syngas from the RSC then flows into a CSC for further cooling to the desired temperature. HP and/or IP steam is generated in the CSC. This design can achieve maximum heat recovery from syngas, resulting in the highest potential overall process efficiency. However, the equipment is bulky and expensive.

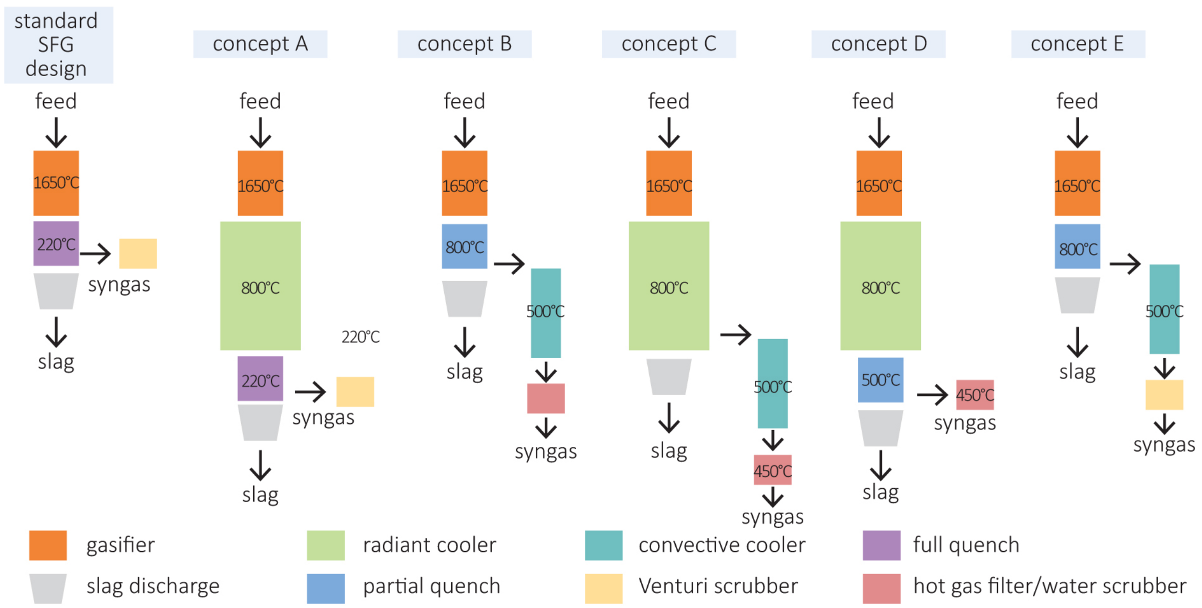

Figure 7 Syngas cooling system designs (Uebel and others, 2014)

3.4.2 Radiant and quench cooling

This design uses a RSC followed by a full water quench cooler. In this design, the hot syngas is cooled initially in a RSC. At the bottom of the RSC, both the molten slag and the raw gas are quenched in the water pool cooler. The cooled slag is removed from the cooler for disposal. The raw gas, saturated with moisture and free of slag particles, flows out of the quench cooler at a temperature of around 200°C. Alternatively, depending on the downstream syngas cleaning/treatment process employed, a partial quench cooler can be used instead of a full water quench cooler. The syngas leaves the partial quench cooler at a higher temperature that is required by the down stream process. The RSC and water quench design has lower costs compared to the radiant and convective design but also has a lower heat recovery rate and therefore, lower efficiency. The RSC and partial quench design has less cooling volume and hence, a smaller quench cooling vessel compared to full water quench.

3.4.3 Partial quench and convective cooling

In the partial quench and convective cooling design, the hot, raw syngas is first quench cooled (using water or gas quenching) to a temperature well below the ash melting point of the coal (usually 800-900°C). After the quench, the syngas enters a CSC and is cooled to the desired temperature while steam is raised. When CO_2 capture is desired, water quench has an advantage over gas quench cooling as the syngas, after water quench cooling, contains a high water content required by the CO shift reaction in the down stream water-gas shift reactor.

Entrained-flow, two-stage gasifiers have been developed which employ chemical quenching in the second-stage gasifier. The sensible heat in the syngas leaving the first stage of the gasifier is used in the endothermic gasification reactions in the second-stage gasification. The syngas exits the gasifier at a temperature of 1000–1100°C and enters the CSC for cooling and heat recovery.

3.4.4 Total quench cooling

In this design, the hot syngas leaves the gasifier and enters a water spray chamber and a slag quench bath. Water is sprayed into the quench chamber to cool the hot syngas. The syngas is forced through or impinges on the water bath surface. The entrained slag is separated from the syngas in the slag quench bath. The water bath level can be adjusted higher or lower to allow the raw syngas to penetrate into the water bath at different depths to further reduce the syngas temperature, augment the water-gas shift reaction, and remove particulates. The raw gas saturated with moisture flows out of the quench cooler at the required temperature.

3.4.5 Quench versus heat recovery

Sensible heat in the hot raw syngas can represent over 15% of the energy in the feed coal. Recovery of this heat from syngas is essential for attaining high process efficiency. Heat recovery systems can reclaim a significant portion of the energy in the feed, depending on the technology employed. However, the syngas cooler is often one of the most expensive items in a coal gasification complex. As in power generation and other industrial processes, there is a trade-off between efficiency and capital cost. The radiant and convective syngas cooling system provides the highest heat recovery rate leading to highest process efficiency. However, the investment cost is significantly higher than for those cooling systems described in Sections 3.4.2 to 3.4.4. The efficiency gain of a coal based IGCC plant using Siemens 500 MWth entrained flow gasifier with a heat recovery syngas cooling system (using either a RSC or CSC) compared to the reference IGCC plant with a total water quench cooling system is shown in Figure 8. It can be seen from Figure 8 that the maximum efficiency gain can be obtained using a radiant cooler. However, a RSC is a large, expensive piece of equipment. As illustrated in Figure 9, a RSC is much taller than the gasifier. The RSC installed in the 250 MWe Polk IGCC plant in Florida (USA), is about 5 metres in diameter and 30 metres tall, and weighs about 815 tonnes (Higman and van der Burgt, 2008).

Nonetheless, the efficiency improvement over a total quench design justifies this expense under certain circumstances and a radiant cooler has been adopted in gasification processes by several developers.

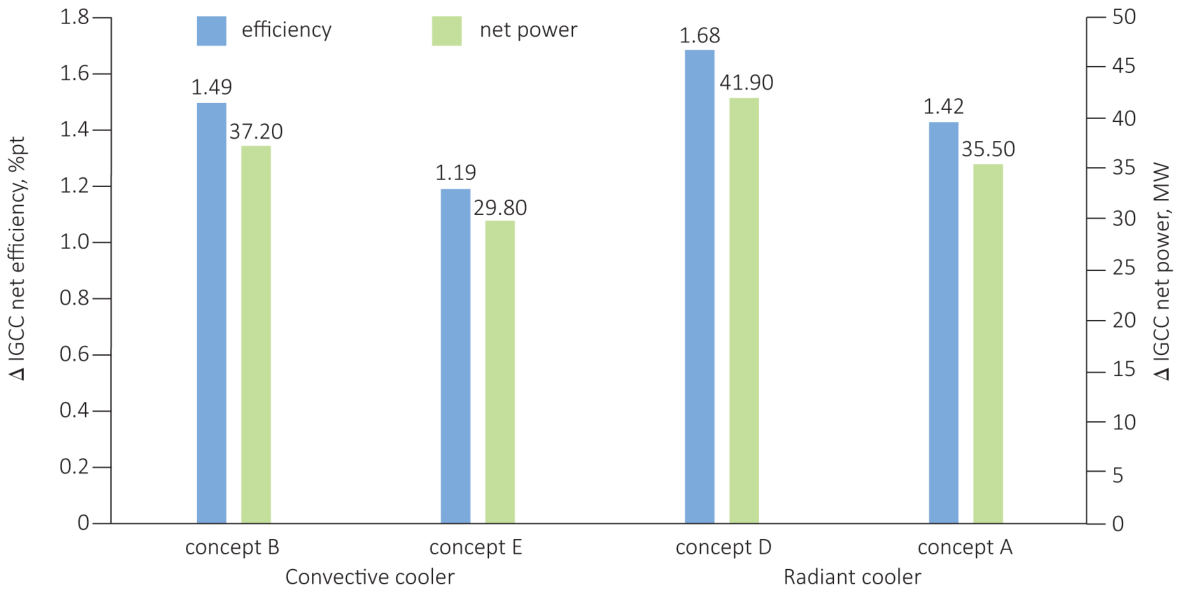

Figure 8 Increases in IGCC efficiency and net power output using syngas cooling systems with heat recovery compared to total water quench (Uebel and others, 2014)

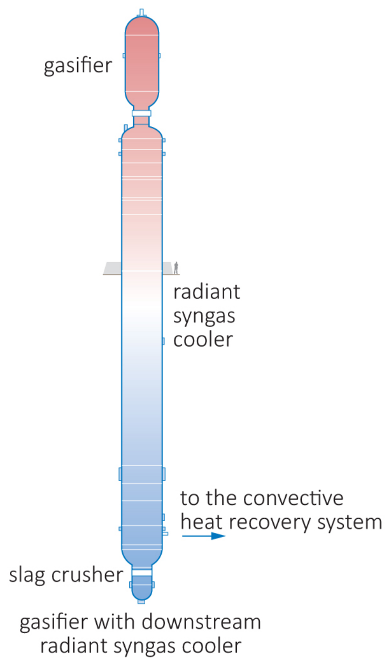

Figure 9 A gasifier with a radiant cooler (Alstom, 2015)

While RSC can only work at high temperatures, CSC is capable of effectively recovering sensible heat in syngas with relatively low temperatures ranged from 300°C to 900°C. A CSC also has a smaller footprint than a RSC. Syngas cooling and heat recovery systems using convective coolers are employed in various gasification processes developed by several companies/developers. However, convective coolers are more sensitive to slag deposition and condensation compared to RSC and quench coolers. They have higher risk of fouling and plugging which can cause a plant trip and high pressure losses leading to increased downtime and higher maintenance costs (Uebel and others, 2014).

There is no heat recovery in the total quench design and the sensible heat of the high temperature syngas is converted to low level process heat rather than high-pressure steam. In spite of the negative impact on efficiency, a total quench cooling system has much lower capital cost and can be justified when low cost feedstock is available. Total quench design is beneficial for the downstream water-gas shift reaction ($H_2O + CO \rightarrow H_2 + CO_2$), which increases the H_2/CO ratio. The saturated syngas exiting a quench cooler has near the optimum H_2O/CO ratio for feed into a water-gas shift reactor. It is used in chemical applications, particularly where a CO shift reaction for hydrogen production is involved. Should CO_2 capture have to be implemented from the beginning of a project (as opposed to being retrofitted later), then this cooling technique would probably be favoured for coal based IGCC applications. Non-quench designs that require CO_2 capture will have to add steam to the syngas before it is sent to a water-gas shift reactor to convert the CO in the syngas to CO_2. Lorenzo and colleagues (2008) analysed the co-production of hydrogen and electricity from coal using the GE entrained flow gasification process and with carbon capture. Their results showed that, compared with total quench cooling, the radiant and convective cooling offered only a modest increase in plant efficiency. They concluded that this efficiency improvement could not justify the cost as the cost of H_2 production would be 10% higher if radiant and convective cooling was used instead of total quench cooling. Results from a more recent investigation into an IGCC power plant with carbon capture showed that when the gas quench and convective cooling system in the standard Shell coal gasifier design is replaced with a water quench cooler, the overall efficiency will be decreased by 1.4 percentage points. However, the Shell IGCC plant with CO_2 capture using a water quench syngas cooling design has significantly lower capital, operating and maintenance costs, leading to a levelised cost of electricity 8.5% lower compared to that of the standard design (Kreutz and others, 2010).

In a total quench cooling system, large quantities of water are used and thus contaminated by the raw syngas, requiring complex waste water treatment. Therefore, the total quench design has additional operating problems such as those caused by corrosion of gasifier walls, increased water treating facilities, increased discharge water permitting issues, and added operating and maintenance costs when compared to radiant and convective cooling designs.

3.5 Comments

Although raw syngas leaving the gasifier is at high temperature, conventional methods for syngas cleaning are typically carried out by scrubbing using chemical or physical absorption processes that operate at low temperatures. After contaminant removal, the syngas has to be reheated prior to its use in a gas turbine or other chemical synthesis process. These process swings adversely impact the plant's energy efficiency and cost. Techno-economic analysis shows that syngas cleaning processes amenable to higher operating temperatures could significantly reduce this efficiency loss and improve the commercial viability of gasification plants. Extensive R&D activities have been carried out in the past three decades to develop high-temperature gas cleaning processes. The focus of most high temperature syngas cleanup has been on the removal of particulates and gaseous contaminants such as sulphur, chloride and alkalis. High temperature particulate cleanup has been one of the most important improvements to commercial syngas applications. Ceramic candle filters emerged as the most promising technology for particulate removal at temperatures up to 1000°C and is subject to intensive investigations. However, there are some fundamental limitations and practical problems with the high temperature application of ceramic candle filters. So far, the operating temperature of ceramic filters is limited to about 400°C or lower. They also suffer low availabilities and reliabilities, and are often one of the major causes of plant downtimes.

It is also critical that, while improving efficiency and reducing cost, the gas cleaning removes a wide variety of coal contaminants such as hydrogen sulphide, ammonia, hydrogen chloride, and carbonyl sulphide, as well as various forms of trace metals to extremely low levels. Accordingly, there has been R&D in this area focusing on the development of high-efficiency processes that operate at moderate to high temperatures and provide multi-contaminant control to protect the downstream units such as gas turbines and catalytic reactors, or to meet stringent environmental standards. These works are currently ongoing.

4 Commercial syngas cooling systems

4.1 Entrained flow gasifiers

The gas cooling requirements for entrained flow gasification processes are more demanding than for other gasification processes due to the higher gasification temperature and the entrained molten ash particles in the raw gas. The key problem is the transition stage between slagging and non-slagging conditions for on cooling the syngas, the entrained ash particles will inevitably pass through the critical temperature range where the ash becomes sticky. This transition temperature range has to be crossed directly after leaving the gasifier, and ideally in such a way that the syngas does not contact the cooling surface before it is sufficiently cooled. Several cooling system designs have been developed to achieve this.

4.1.1 GE Energy gasification process

The GE Energy (formerly Texaco) process for coal gasification uses a slurry feed, downflow, entrained flow gasifier. The reactor shell is an uncooled refectory lined vessel. The coal is gasified at a high pressure of 3.5–8.6 MPa and a temperature of 1315–1480°C. The raw syngas is composed primarily of hydrogen, carbon monoxide, carbon dioxide and water (EPRI, 2006). GE Energy offers a number of syngas cooling concepts, including a radiant and convective design, a radiant and water quench design, and a total water quench design. The selection between these three alternatives is a matter of economics for specific applications. For its standardised 630 MWe reference IGCC plant GE Energy has chosen the radiant-quench configuration.

Radiant and convective cooling design

This design makes the full use of the potential for heat recovery for maximum efficiency and has been adopted in Cool Water and Polk IGCC plants. In this design (*see* Figure 10) the gasifier is located vertically above a radiant cooler. The hot syngas leaves the gasifier at the bottom and flows downward through the radiant cooler where it is cooled. High pressure steam is generated in tubes built into the heat transfer surface at the perimeter of the cylindrical gas flow zone. Additional heat transfer surface is provided by radial platens (wing walls) from the water walls at the perimeter of the vessel. Sootblowers can be provided to remove any accumulations on the tube water walls. The molten slag falls into the quench bath at the bottom of the cooler, where it solidifies and is removed via a system of lock hoppers for subsequent disposal.

Syngas leaves the radiant cooler at around 760°C and flows through a transfer duct to the convective syngas cooler where additional high pressure steam is generated. In the CSC, the syngas flows across the boiler tube banks. These tubes help remove the entrained particles in the syngas that are too fine to drop out in the bottom of the radiant cooler. The raw gas leaves the CSC at 315–425°C and flows to the gas scrubbing unit for removal of remaining particulate matter and chlorides. Several different designs of convective coolers have been installed at various locations including water tube and fire tube designs and horizontal, vertical upflow and downflow configurations. The Cool Water project had an upflow duct followed by downflow over boiler tube banks, whilst at Polk IGCC plant, the syngas flow from the bottom of the radiant cooler is split into two parallel horizontal fire tube convective exchangers (EPRI, 2006; Higman and van der Burgt, 2008).

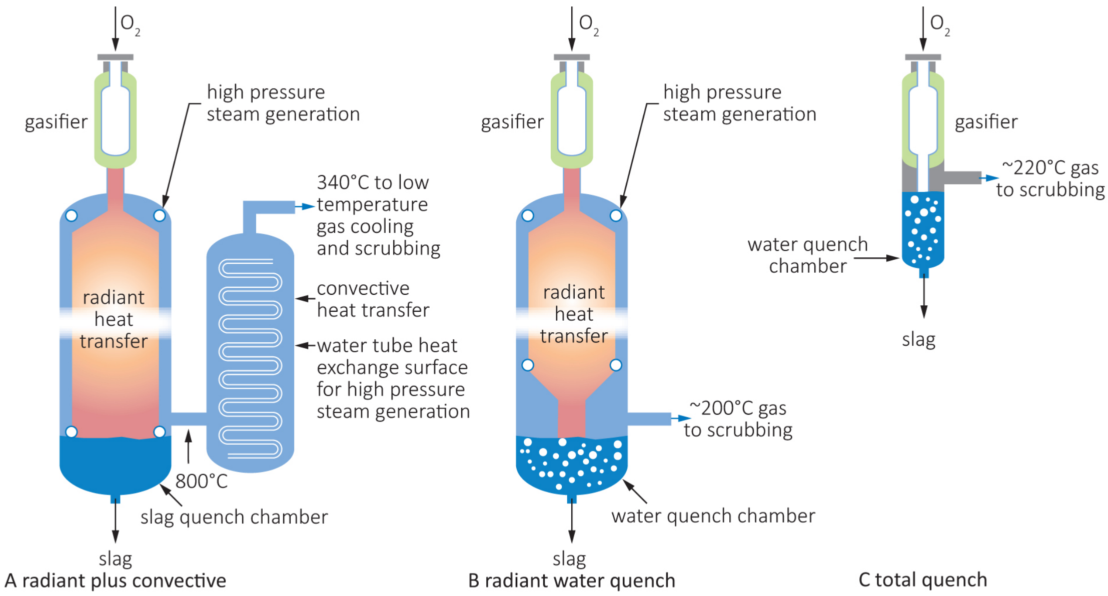

Figure 10 Syngas cooling options for GE process (Koppel and Lorden, 2009)

Radiant and water quench design

In this design, the hot raw syngas leaving the gasifier flows downwards into the same radiant cooler described above and is cooled by generating high pressure steam. However, at the bottom of the radiant cooler both the raw gas and the slag are quenched in water and cooled. Slag and any unconverted char are removed from the bottom of the quench chamber via a lock hopper system as previously described. The raw gas saturated with moisture then flows to the gas scrubbing unit at a temperature of 200–220°C for further removal of particulate matter and chlorides (EPRI, 2006; Rubin and others, 2007). This design concept has been applied to the syngas cooling system at Duke Energy's coal-fuelled 613 (net) MWe Edwardsport IGCC plant in Indiana (USA), which began commercial operation using natural gas in 2013.

Total quench design

In this design, the gasifier is directly connected to the quench chamber, making a compact configuration (*see* Figure 10). The hot syngas and the molten slag particles flow downward through a water spray chamber and a slag quench bath. Water is sprayed just beneath the partial oxidation chamber to cool the hot syngas. The entrained slag is separated from the syngas in the slag quench bath. There is no high pressure steam generation in this method as in the previous two designs. The raw gas saturated with moisture flows to the gas scrubbing unit at a temperature of 205–260°C depending on the pressure (EPRI, 2006; Rubin and others, 2007).

4.1.2 The Shell coal gasifier

The Shell Coal Gasification Process (SCGP) uses a dry-feed, pressurised, oxygen-blown, up-flow, entrained-flow gasifier. Figure 11 shows a simplified SCGP flow sheet. The gasifier features a refractory-lined reactor vessel, equipped with an inner membrane wall consisting of circulating water/steam-filled tubes. Inner reactor wall temperature is controlled by circulating water through the membrane wall, producing steam. Dried, pulverised coal is fed via two feed injectors to the opposite sides of the gasifier, near the bottom, through pressurised lock hoppers using a transport gas (syngas or nitrogen). Preheated oxygen and steam are mixed and fed to the gasifier via the same injectors or below the coal injection points. Shell coal gasifiers typically operate at a pressure range of 2–4 MPa. The temperature of the gasifier is kept within the range of 1400–1700°C by adjusting the flow rates of coal, oxygen and steam. Most of the ash forms slag inside the gasifier at these high temperatures and then flows down and exits from the bottom of the gasifier. The syngas produced consists primarily of carbon monoxide and hydrogen (typically around 60% CO and 30% H_2). The hot syngas flows upward out of the gasification zone with part of the molten ash entrained. The syngas cooling system is an integral part of Shell gasifier technology.

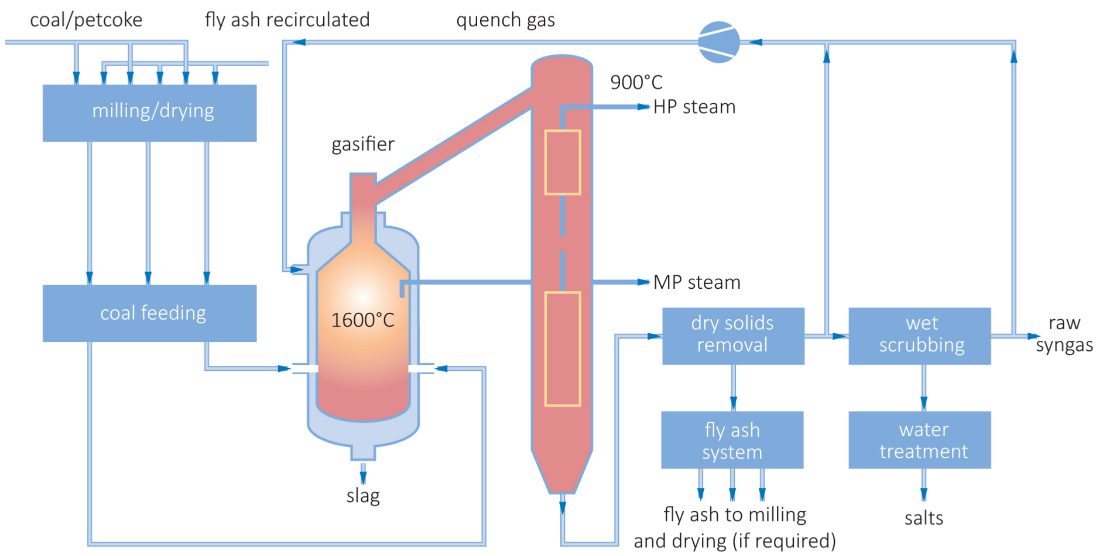

Figure 11 Simplified Shell coal gasification process (de Graaf, 2008)

Gas quench and CSC design

At the top of the gasifier the raw syngas enters the quench zone where it is quench cooled from 1500–1600°C to about 900°C with cold, dust-free recycled syngas of about 250°C, to ensure that the entrained molten fly slag is solidified prior to entering the CSC. The quench is designed in such a way that the hot gases and the slag do not come into contact with the wall before they are cooled to a temperature where the slag becomes non-sticky. The gas quench section is connected through a steam-cooled duct to the CSC. The CSC is a water tube boiler in which the syngas flows from the top downward (*see* Figure 12). The CSC consists of economisers, medium- and high-pressure evaporators, and some superheaters. The vessel wall is protected from direct contact with the hot gas by wall heating surfaces. The main heating surfaces consist of concentric cylinders of helical coiled tubes installed within the wall panels. To facilitate mechanical cleaning (with rappers) of the cylinders, the tubes are welded together to form a membrane. The steam conditions in the syngas cooler are 12 MPa and 400°C. In principle, the steam conditions could reach 13.9 MPa and 540°C. However, it is usually determined that, for an IGCC plant, the superheating of the high-pressure steam can be more economically accomplished in the Heat Recovery Steam Generator (HRSG) at the gas turbine exhaust rather than in the more aggressively corrosive atmosphere at the top of the syngas cooler. The saturated steam conditions in the syngas cooler can be as high as 12.5 MPa and 400°C, in which case a metal with a high chromium content would have to be chosen for the high pressure cooling surfaces. Depending upon coal prices, it may be more economic to raise steam at a lower pressure of 5 MPa when a lower cost ferritic material can be selected for the medium pressure surfaces (EPRI, 2006; NETL, http://www.netl.doe.gov/).

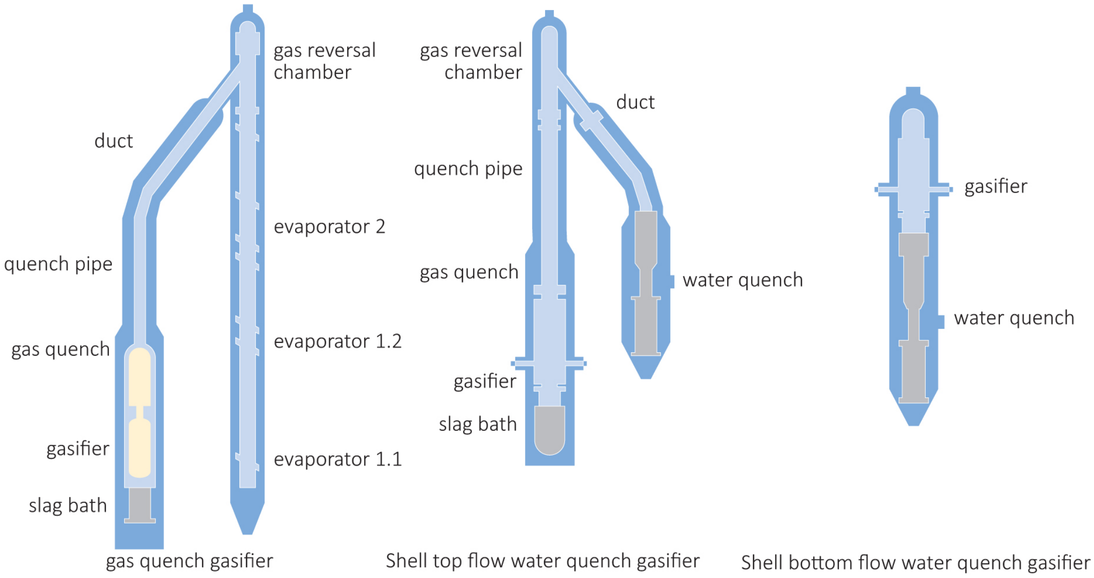

Figure 12 Syngas cooling options for SCGP (van Paasen and others, 2012)

The syngas leaves the CSC at a temperature of around 250–300°C and enters the fly ash removal system, where the majority of the fly ash contained in the gas is removed. After fly ash removal, a portion (about 50%) of the solids free gas (<5 mg/m^3) is compressed and recycled as quench gas to the top of the gasifier. The balance of the gas is sent to a wet scrubber to remove any remaining fly ash and is then sent to the acid gas removal system.

The Shell SCGP with gas quench and CSC cooling system was commercially demonstrated at Nuon Power's decommissioned Buggenum IGCC plant in the Netherlands. The plant was capable of gasifying 2000 tonnes of coal per day to produce 253 MWe of net electricity.

Top flow water quench cooling design

Recently, Shell has introduced a partial water quench cooling system to replace the CSC. With this design, the gasification process remains the same as that described above except that the CSC is replaced by a water quench cooler, and the dry solids removal is replaced with a wet fly ash removal unit. The hot, raw syngas leaving the gasification zone is initially quench cooled by recycled, cold syngas before entering the water quench cooler. The syngas then flows from the top downward to the water quench cooler, which is a wide empty vessel that is located below the gas reversal chamber (*see* Figure 12). Water at about 230°C is sprayed into the vessel, near the top, via proprietary designed nozzles to produce a fine mist for optimum water evaporation and syngas cooling. The cooled syngas exits the water quench cooler at a temperature of approximately 425°C.

The SCGP with partial water quench has a simpler system design and smaller footprint, and therefore lower capital cost compared to that of SCGP with gas quench and CSC cooling system. It improves the fuel flexibility by enabling gasification of coals that cannot be processed with a CSC due to fouling. It is also advantageous when CO shift is planned immediately downstream of the gasifier due to its better integration with a downstream shift reactor (Fournier G, 2009; de Graaf, 2008).

Bottom flow water quench cooling design

Shell has been working to reduce the capital cost of SCGP, which has led to the more recent development of the Shell coal gasifier with a bottom water quench cooling system, a cooling concept similar to the total quench cooling design adopted by the GE process discussed in Section 4.1.1. With this cooling concept, the gasifier design needs to be modified. As shown in Figure 13, the gasifier is now downflow with coal and the mixture of oxygen and steam being injected near the top of the gasifier. The gasifier design retains most of the features of the previous Shell coal gasifiers such as membrane wall, dry feed and multi-burners. However, gas quench cooling is eliminated. The hot syngas and molten slag flow downward and exit the gasifier from the bottom. The syngas and molten slag then enter the water quench chamber that is located underneath and is directly connected to the gasifier. There is a quench bath at the bottom of the cooler and water is sprayed from the top into the quench chamber to cool the hot gas. The syngas then passes into the water bath where it is separated from slag and becomes saturated with moisture (van Paasen and others, 2012).

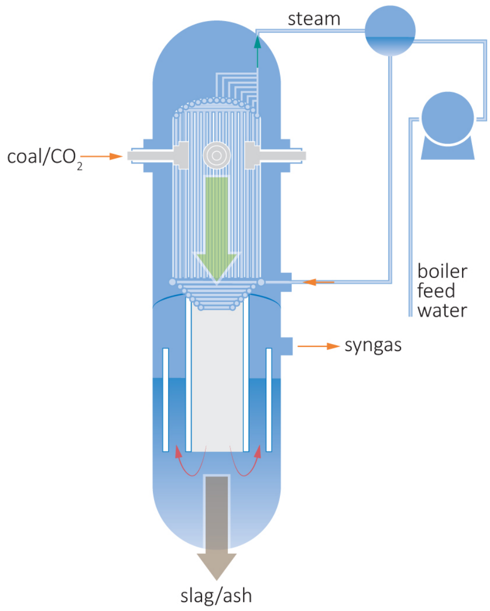

Figure 13 Bottom-quench SCGP gasifier and water quench cooler design (van Paasen and others, 2012)

The SCGP with bottom quench has the simplest process configuration and much smaller footprint compared to the SCGP with the other two cooling system designs (*see* Figure 12). This means less steel, less equipment, and a shorter manufacturing time, which substantially reduces capital costs (by up to 30%). It is more fuel flexible but has a lower energy efficiency. In 2013, Shell and Chinese Wison Engineering successfully started a 1000 t/d SCGP bottom-quench technology demonstration plant in the Nanjing Industrial Park, which had 99% carbon conversion. In January 2014, a Chinese company Hulunbeier Jinxin, a subsidiary of the Yuntianhua Group, signed a licensing agreement for a bottom-quench gasifier to process lignite feedstock (van den Berg and others, 2014).

4.1.3 The PRENFLO gasifier

Developed by Krupp Koppers and currently offered by Uhde (Krupp Koppers merged with Uhde in 1997), the PRENFLO technology shares many common features with Shell SCGP. Both employ dry feed using similar pneumatic conveying feed systems and opposed fuel injectors, multiple burners and a membrane wall. The PRENFLO gasifier operates at elevated pressure (≥4 MPa) and gasification temperatures of >2000°C. The syngas temperature at the gasifier outlet is in the range of 1350–1600°C. The PRENFLO gasifier is offered with two cooling options, the PRENFLO with steam generation (PSG) and PRENFLO direct quench (PDQ).

PRENFLO PSG cooling system is integrated with and is located on top of the gasifier. It consists of an upflow/downflow (two pass) gas quench pipe and water tube CSC as illustrated in Figure 14. Pulverised coal and oxygen or oxygen/steam mix are injected near the bottom of the gasifier and flow upward through the gasifier. The hot raw syngas exits from the top of the gasifier and enters the quench chamber where it is cooled to around 800°C by mixing directly with a quench gas at

235°C. The cooled syngas flows up, leaves the quench chamber from the top and then flows down through the CSC. The syngas is further cooled in the CSC while producing high-pressure steam. The syngas exits from the bottom of the CSC at a temperature lower than 470°C and enters a second, external CSC where it is cooled to a temperature around 235°C. Medium-pressure steam is generated in the second CSC (Coca, nd).

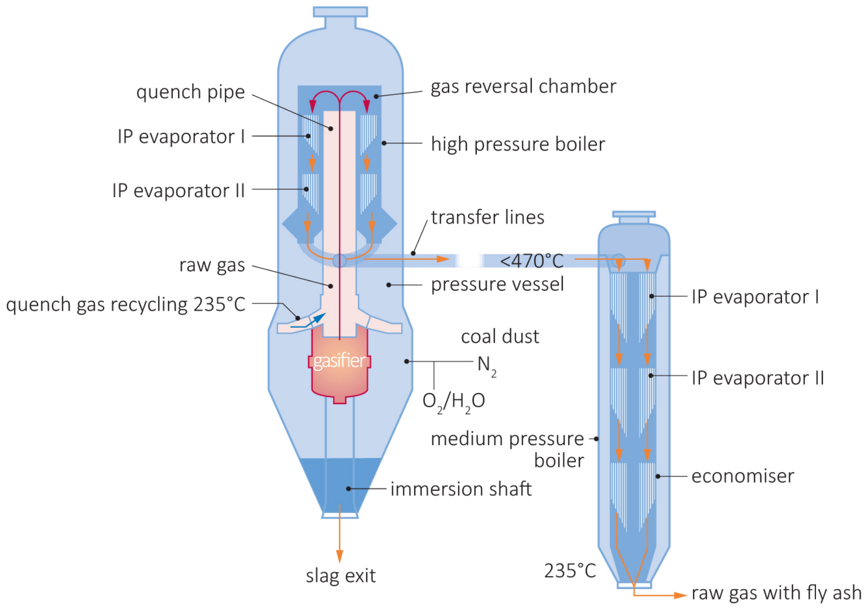

Figure 14 PRENFLO PSG cooling system (Coca, nd)

PRENFLO PSG technology is used at the 300 MWe Puertollano IGCC power plant, Spain. This plant operates with a mixture (50:50) of petroleum coke and coal.

Similar to the Shell's bottom-quench SCGP, PRENFLO PDQ uses a full water quench cooler that is located underneath and is directly connected to the gasifier. Pulverised coal and oxygen or oxygen/steam mixture are injected near the top of the gasifier. The hot syngas and molten slag flow downward, exit the gasifier from the bottom and then enter the water quench chamber. There is a quench bath at the bottom of the cooler and water is sprayed from the top into the quench chamber to cool the hot gas. The syngas then passes into the water bath where it is separated from slag and become saturated with moisture. The cooled syngas leaves the quench cooler at a temperature of 200–250°C (Thyssenkrupp, 2015).

4.1.4 The E-Gas gasifier

Currently owned by CB&I, the E-Gas gasifier is a slurry fed, oxygen blown, pressurised, upflow, entrained flow slagging gasifier. The E-Gas gasifier consists of two stages, a slagging first stage and a non-slagging second stage as shown in Figure 15. The unique two-stage operation facilitates chemical quench cooling of the syngas in the second stage.

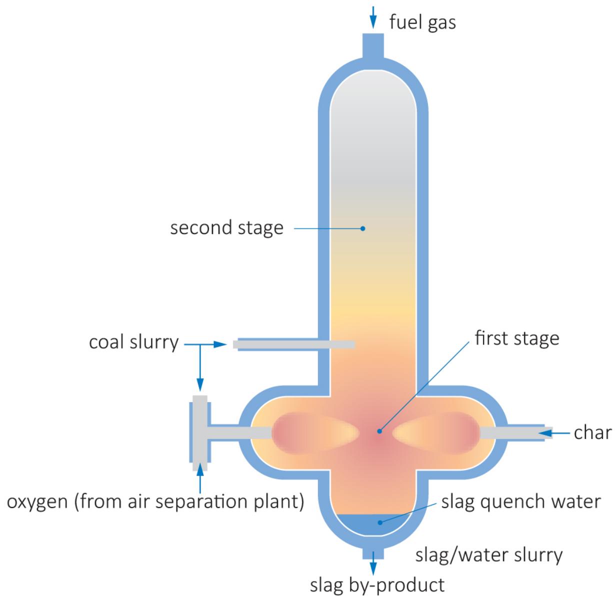

Figure 15 E-Gas gasification process

In the current standard IGCC design, about 70–75% of the total slurry feed is fed along with oxygen to the first (or bottom) stage of the gasifier through two opposing mixing nozzles, one on each end of the horizontal section of the gasifier. The first stage is a horizontal, refractory-lined vessel with two horizontally opposed burners. This stage involves highly exothermic oxidation reactions and operates at 1400°C and 2.8 MPa typically. The gasification/oxidation reactions take place rapidly and the coal is almost totally gasified in this environment to produce the raw syngas consisting principally of H_2, CO, CO_2 and H_2O. Ash in the coal melts and flows out of the bottom of the gasifier vessel as slag. The hot raw syngas generated in the first stage flows up from the horizontal section into the second (top) stage of the gasifier. The second stage is a vertical refractory lined vessel in which the remaining slurry is added which reacts with the hot syngas stream exiting the first stage. The coal undergoes devolatilisation, pyrolysis and partial gasification thereby generating additional syngas with a higher heating value since no additional oxygen is introduced into the second stage. The endothermic gasification/devolatilisation reactions in this stage reduce the final gas temperature to about 1000–1050°C. Unreacted coal (char) is carried over with the syngas.

The hot raw syngas with entrained particulate matter exiting the gasifier is cooled from 1040°C to 370°C in a convective syngas cooler. The syngas cooler is a vertical fire-tube heat recovery boiler. This unit generates saturated high-pressure steam, up to 13 MPa. Steam from the high-temperature heat recovery system is superheated in the gas turbine heat recovery system for use in power generation. Alternatively, syngas can be superheated to more modest temperatures of 400-420°C in the syngas cooler (EPRI, 2006; Wabash River Energy/US DOE, 2000).

The E-Gas coal gasification technology is incorporated in the Wabash River Coal Gasification Repowering Project, funded under the DOE Clean Coal Demonstration Program in the 1990s. The Wabash IGCC plant, which runs on bituminous coal, has been in operation since 1995.

4.1.5 Other entrained flow gasifier cooling systems

The MHI gasifier

The basic concept of the MHI (Mitsubishi Heavy Industries) gasifier is similar to the E-gas gasifier. The MHI gasifier is a pressurised, air-blown, upflow, slagging reactor with a two-stage operation. The MHI gasifier, however, uses a dry-feed system and the reactor internal is protected by a membrane wall, similar to those of the Shell and Siemens designs but with no refractory. The reactor operates at a pressure around 2.6 MPa and consists of two sections (or stages): a lower combustor and an upper reductor, as illustrated in Figure 16. Dry pulverised coal is fed at two separate points into the gasifier with a portion being fed into the combustor together with air (or oxygen enriched air) where it is burned to produce CO and CO_2, as well as H_2O. The temperature inside the combustor is extremely high at about 1800°C so the ash melts and flows down. The molten slag falls to the bottom of the gasifier where it is quenched in a water bath and then removed using a lock hopper system. The gas produced in the combustor rises to the reductor where the remaining coal is added, without any additional air. At the reductor stage, heat provided by the hot gas from the combustor is used to drive the endothermic gasification reactions, lowering the temperature in the reductor by about 700°C (*see* Figure 16). The coal is devolatilised and tars are cracked sufficiently and hence no problems occur in the downstream fire-tube CSC. Any molten ash carried over by the upward gas is solidified. The syngas produced exits the reductor at a temperature between 1000–1100°C and then enters a high temperature syngas cooler that is an integral part of the gasifier. High-pressure steam is produced, which is sent onto the downstream HRSG unit for superheating. A cyclone is used downstream of the syngas cooler to collect the chars and recycle them to the combustor section to increase the overall carbon conversion efficiency (Nunokawa and Asano, 2014; Hashimoto and others, 2010).

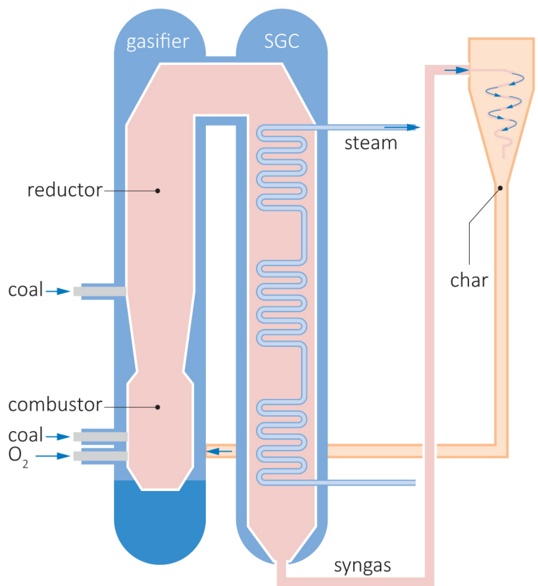

Figure 16 MHI gasifier integrated with a CSC (Loney and others, 2012)

The MHI gasification technology has been demonstrated in the Nakoso (Japan) 250 MWe IGCC plant. The demonstration completed in 2013 and the Nasako IGCC plant has since been in commercial operation.

The current focus of the effort is on air-blown (or enriched air blown) IGCC application. R&D activities are being carried out to develop an oxygen-blown system for coal to fuels and chemicals applications.

The EAGLE gasifier

The Electric Power Development Corporation (Japan) has been working on developing the EAGLE gasifier, which is a pressurised, single-chamber two-stage spiral-flow gasifier with water-cooled membrane wall. Similar to the E-Gas gasifier and MHI gasifier, the EAGLE gasifier is a two-stage reactor but it operates with a dry feed and in an oxygen-blown mode. Another unique feature of the EAGLE gasifier is its tangential feed injection and burner system, as shown in Figure 17a, which allows a spiral flow pattern to be developed along the inter-reactor wall between the upper and the lower reactor stage, resulting in a higher overall gasification efficiency due to the longer residence time and more efficient slag removal.

Figure 17b shows an EAGLE gasifier vessel with a radiant cooler on top of the gasifier reactor. The gasifier operates at 2.5 MPa and has four coal burners at each stage as well as two char burners in the lower (first) stage. About equal quantities of pulverised coal is injected into both lower and upper (second) stage of the gasifier. The gasification reaction is controlled by adjusting the oxygen flow rate into the two stages. The first stage operates in an oxygen rich mode at a temperature of around 1600°C. The combustion gas produced in the lower stage rises into the upper stage where the hot gas drives the endothermic gasification reactions to produce syngas. The upper stage operates in oxygen lean and non-slagging mode. The particulate matter in the syngas contains unreacted char and ash. They are removed from the raw syngas downstream of the syngas cooler and recycled back to the first stage.

The hot syngas leaving the gasifier reactor at a temperature of around 1150°C is quenched with recycled, cooled syngas. Up to 10% (by volume) of recycled syngas from the outlet of the primary water scrubber is introduced at the throat section of the gasifier into the stream of the hot raw syngas to prevent slagging and fouling in the downstream syngas cooler. The quenched syngas flows up through the heat exchanger in the upper part of the gasifier where the heat in the syngas is recovered by producing high-temperature, high-pressure steam. The syngas leaving the gasifier vessel then enters a CSC where it is further cooled to a temperature of around 350-400°C (Tajima and Tsunoda, 2002; Nagasaki and others, 2013).

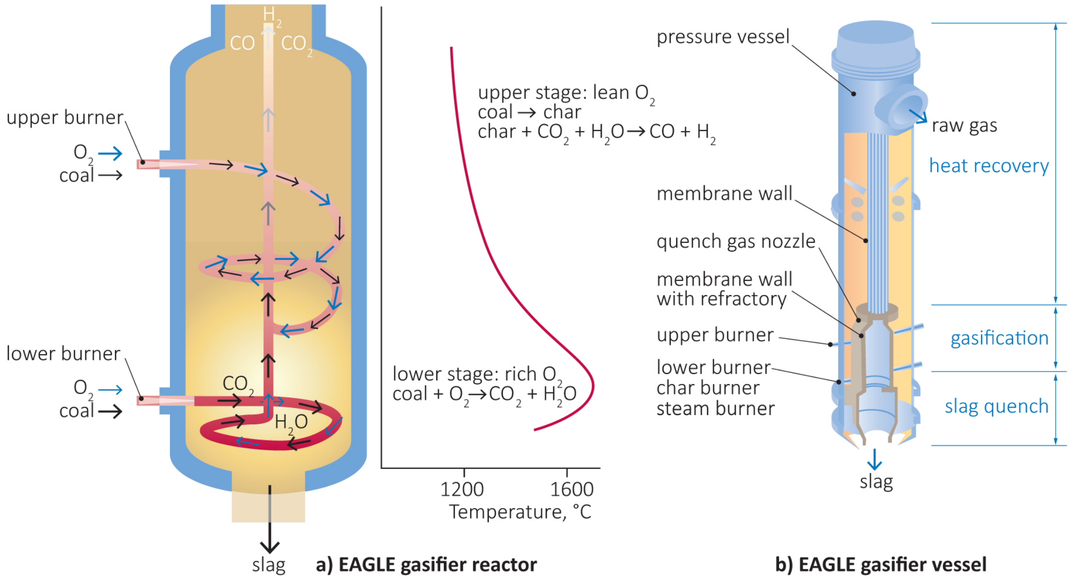

Figure 17 Simplified drawings of the EAGLE gasifier

The EAGLE technology is currently being demonstrated in a 150-t/d pilot plant facility at J-Power Wakamatsu Research Institute in Kitakyushu City, Japan.

Siemens Fuel Gasifier (SFG)

Formerly Future Energy/GSP/Noell, the SFG is a dry-feed, pressurised reactor, which can be supplied with either a refractory lining for low ash (<2% by weight) feedstocks or with a cooling screen in the gasification section of the gasifier. The reactor with cooling screen and pneumatic dense flow feeding system is the preferred design for coal, resulting in high carbon conversion efficiencies (>98%). The cooling screen consists of a gas-tight membrane wall covered with a SiC castable onto which a layer of molten slag is deposited. Coal together with oxygen and steam is supplied via top-mounted burners and flows downwards in the reaction chamber. Gasification takes place at temperatures of around 1300°C to 1800°C and a pressure of ≥4 MPa. Depending on the application, the gasifier can use either total or partial quench cooling. The cooling concepts are similar to the radiant and water quench design and the total quench design adopted by GE. With the total quench cooling design, raw gas and slag exiting the gasifier enter a quench chamber that is arranged beneath the reaction chamber. By injection of water the gas is cooled to temperatures of around 220°C and the molten slag solidifies (Siemens, 2012).

For IGCC plants with carbon capture and storage (CCS), a syngas cooler design with heat recovery and partial water quench cooling has advantages in conjunction with the CO-shift for pre-combustion CO_2 removal. Siemens has been investigating cooling concepts that integrate heat recovery and cooling of high temperature syngas and has recently concluded that concept A illustrated in Figure 7 is advantageous for an optimised and economic gasification process. With this cooling concept, the gasification vessel consists of a gasifier, a radiant cooler and a water quench vessel. The raw, hot syngas exits from the bottom of the gasifier and flows down through the radiant cooler where it is cooled from around 1650°C to about 800°C. The syngas then enters the water quench chamber and is cooled to a temperature of around 220°C (Guenther, 2012; Uebel and others, 2014).

4.2 Fluidised bed gasifiers

4.2.1 KBR Transport Integrated Gasifier (TRIG)

As described in Section 2.2.3 the TRIG is a circulating fluidised bed reactor that operates in either air- or oxygen-blown mode. As illustrated in Figure 18, the gasifier consists of an assembly of refractory-lined pipe that includes a mixing zone, riser, solids separation and collection unit, and solids recycle section. Steam and air/oxygen are mixed together and introduced in the lower mixing zone while fuel, sorbent (for sulphur capture) and additional air or oxygen and steam are added in the upper mixing zone. The steam and air/oxygen, fuel, sorbent, and solids from the standpipe are mixed together in the upper mixing zone. The gas and solids move up the riser before entering the disengager which separates larger particles by gravity. Most of the solids flow from the disengager into the standpipe, while the remaining solids flow to the cyclone and are removed. The gas exiting the gasifier enters a high temperature syngas cooler to lower the gas temperature before it enters a particulate filter system to remove the remaining fine particulate matter.

TRIG has an operating temperature of approximately 954°C (1750°F) for Powder River Basin (PRB) subbituminous coal and lignite and operating pressure up to 2 MPa. For a coal-to-SNG (substitute natural gas) process, the raw, hot syngas containing a small amount of fine particulate exits the TRIG at 900-925°C (1650-1700°F) and is cooled to about 370°C (700°F) in a CSC. As shown in Figure 19 the CSC consists of three heat exchange stages: steam generator, superheater and economiser. The first stage of the syngas cooler is the steam generator. Here, HP steam is produced while the syngas is cooled to approximately 730°C (1350°F). The middle section of the syngas cooler is the superheater, where HP steam from the steam drum within the syngas cooler along with 8.6 MPa saturated HP steam from the downstream methanation process is superheated to 510°C (950°F). The final section of the syngas cooler is the economiser, where the syngas is cooled to about 370°C (700°F). Boiler feed water enters the economiser at 195°C (385°F) and 8.6 MPa. Water is then heated to about 300°C (574°F) and flows to the HP steam drum (Ariyapadi and others, 2009).

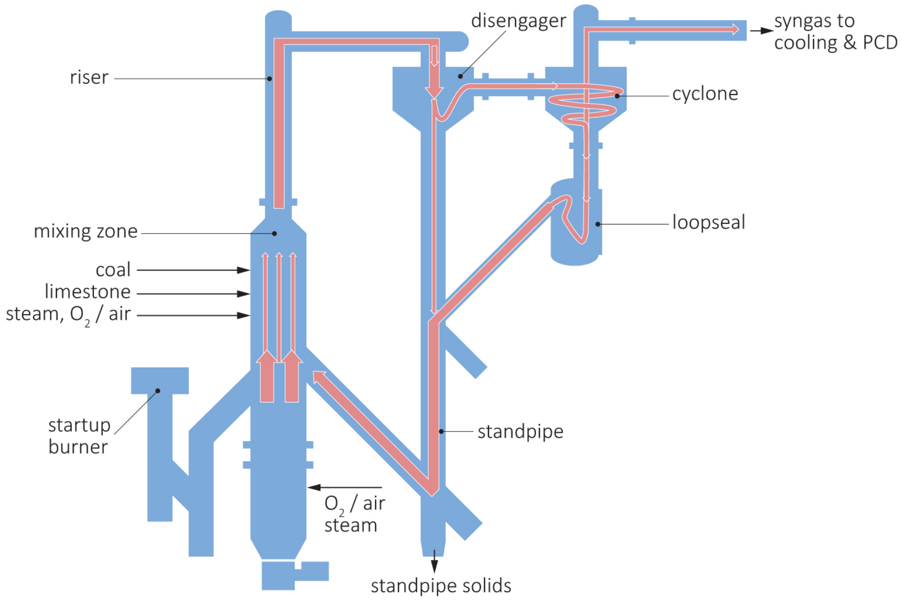

Figure 18 KBR Transport Integrated Gasifier

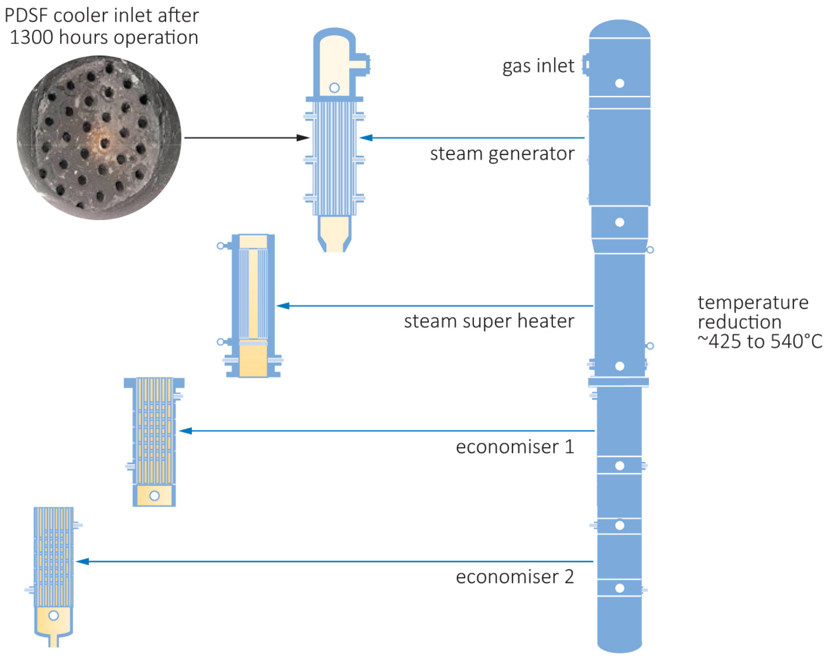

Figure 19 High temperature syngas cooler at Kemper IGCC plant (Southern Company, 2010)

Similarly for an IGCC process, the syngas cooler also consists of three stages: an evaporator, a superheater and economisers. The evaporator includes a natural circulation steam drum operating at above steam turbine inlet pressure and at saturated temperature. The steam raised in the evaporator is passed to a superheater that heats the steam to the steam turbine inlet temperature. This steam would be mixed with superheated steam exiting the combined-cycle unit's HRSG before passing into the steam turbine. Boiler feedwater enters the economisers and is heated to near saturation before entering the steam drum (DOE/USACE, 2010; Southern Company, 2010).

The TRIG technology has been selected for the Kemper County Project (also called the Kemper County Energy Facility), which is a lignite fuelled IGCC power generating plant and will be owned and operated by Mississippi Power, a subsidiary of Southern Company (USA). The plant design incorporates two air-blown TRIG gasifiers with a net capacity of 582 MWe, and carbon capture technologies to capture at least 65% of CO_2. The construction started in 2010 and the plant is expected to start commercial operation in 2016 (http://www.mississippipower.com/).

4.2.2 High Temperature Winkler (HTW) Gasifier

Developed by Rheinbraun AG (now RWE) and acquired by ThyssenKrupp Uhde in 2011, the HTW gasifier is a circulating fluidised bed reactor which operates in either air- or oxygen-blown mode. It is a dry-feed, pressurised, dry ash gasifier and can operate at 800–1000°C and 1–3 MPa. The temperature is controlled to ensure that it does not exceed the ash softening point. A key advantage of the technology is the capability to gasify a variety of different feedstocks, including all grades of more reactive low-rank coals with a higher ash softening temperature such as lignite, and also various forms of biomass. Due to the relatively high gasification temperature, the syngas does not contain any higher molecular weight hydrocarbons such as tars, phenols, and other heavy aromatics. The raw syngas exiting the gasifier is cooled in a CSC from approximately 900°C to around 300°C. An HTW demonstration plant (25 t/h dry lignite or 140 MWth) was built at Berrenrath (Germany) which was operated for over 10 years from 1986 to 1997. The design of the water tube cooler employed at the HTW demonstration plant is shown in Figure 20. The raw syngas with a temperature of approximately 900°C and a particulate content of around 30g/m^3 was cooled in the syngas cooler. Saturated steam of 360°C and 1.8 MPa was generated, which was further heated to become superheated steam with a temperature of 580°C and a pressure of 3.5 MPa (Bassett, 2012; Renzenbrink W and others, nd).

A horizontal fire tube cooler was also tested at the demonstration plant. Test results showed that both the water tube cooler and fire tube cooler could be employed to meet the cooling requirement. With optimised design and operating conditions, dust deposition and/or caking, fouling as well as erosion and corrosion can be minimised. The developer recommends that the water tube cooler be utilised for IGCC applications where supercritical steam conditions are used to optimise the overall process efficiency, whilst for applications that require medium-pressure steam (<15 MPa), the fire tube cooler should be used for cost reasons (Renzenbrink W and others, nd).

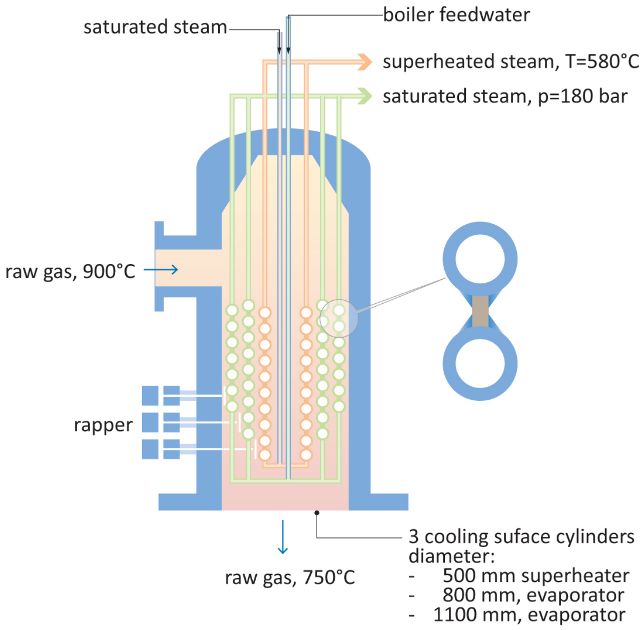

Figure 20 Design of the water tube cooler employed in the HTW demonstration plant (Renzenbrink W and others, nd)

4.2.3 Syngas cooling system for other fluidised bed gasifiers

Several fluidised bed gasification processes have been developed and are in commercial operation for power generation and production of synthetic fuel and chemicals. More fluidised bed gasifiers are under development. Fluidised bed gasifiers are operated under non-slagging conditions. The operating temperature of fluidised bed gasifiers, which is typically in the range of 900-1100°C, is sufficient to achieve high carbon conversions while mitigating formation of tars and oils. The syngas exiting the fluidised bed reactor, usually free of tars and with low fly ash content, has a temperature of 800–1000°C which does not raise any major technical challenges for cooling systems. Depending on the application and downstream gas cleaning processes, this hot, raw syngas can generally be cooled either by a CSC or a quench cooler. For IGCC plants, syngas cooling and heat recovery are preferred in order to achieve higher plant efficiency. Standard engineering design for heat recovery steam generators can be applied. For example, the U-Gas technology is used in the Zao Zhuang facility (ZZ Plant) to gasify low rank and waste coal to produce low-to-medium heating value syngas, and in Yima coal-to-methanol plant (both in China). Industrial HRSG are used to cool the high temperature raw gas while producing high- and medium-pressure steam that is sent to the gasifier as gasification agent. Steam generated from the HRSG that is not used by the gasification process is exported to meet other plant needs (SES, 2013; Khan and Lau, 2012).

One exception is the IDGCC (Integrated Drying Gasification Combined Cycle) process under development by HRL Pty Ltd (Australia). IDGCC is a fluidised bed gasification process designed specifically for the high moisture brown coal in Victoria, Australia. The Victorian brown coal has a very high moisture content of around 60% but very low ash content of <1%. The IDGCC process consists of an air-blown, pressurised fluidised bed reactor with an integrated drying process. In the IDGCC process, hot syngas produced in the gasifier is used to dry the incoming raw coal under pressure, in a direct contact entrained flow dryer. The heat of the syngas dries the coal whilst the evaporation of the coal moisture cools the syngas eliminating the need for expensive high temperature heat exchangers for the syngas cooler. The preheated dry coal is gasified in the gasifier, which operates at a temperature of 900°C and pressure of 2.5 MPa. The cooled raw gas is first cleaned in a cyclone and then by a ceramic filter (Blatchford, 2011). The developer is now seeking to build a commercial scale IDGCC demonstration plant.

5 Operating experiences

5.1 Cool Water IGCC demonstration plant

As part of DOE's CCT Program, the Cool Water Project was the first successful demonstration of the IGCC concept at a commercial scale. The five-year R&D project ran from 1984 to 1989 in Southern California, USA. GE Energy's (formerly Texaco) gasification technology was used to produce syngas to feed a GE-7E gas turbine based combined cycle. A net power generation capacity of 96 MWe was achieved using bituminous coal as a fuel and 99.5% pure oxygen as the oxidant.

Gasification of coal took place at a temperature range of 1260–1538°C (2300–2800°F) and a pressure of 4 MPa. The radiant and convective cooling concept (*see* Section 3.4.1) with an upflow duct followed by downflow over boiler tube banks design was adopted. The syngas produced consisted mainly of CO, H_2, CO_2, and H_2O as well as some unconverted carbon and slag. Fuel-bound sulphur was converted primarily to H_2S with some COS formed. Fuel-bound nitrogen was largely converted to N_2 with some NH_3 formed. The hot, raw syngas was first cooled in the radiant cooler that generated 11 MPa saturated steam. The slag solidified and dropped into a water sump at the bottom of the vessel where a lockhopper system was used for its removal. The raw syngas was then cooled further in the convective cooler, generating additional 11 MPa saturated steam and preheating the boiler feed water.

A quench gasifier was added to ensure continuous operation if the main gasifier was not available. Quench gasifier operation was similar to main gasifier operation except heat recovery via steam generators was not provided in the quench system. Instead, the hot raw syngas was immediately quenched with water as soon as it left the gasifier and the syngas went directly to a wet scrubber for particulate removal.

Steam produced by the syngas coolers was combined with steam raised in the HRSG prior to the superheater section. The combined, superheated steam was then sent to the steam turbine-generator.

This demonstration project was considered a success and the operation, in general, was smooth as fewer difficulties than expected were encountered. Early in the programme, fouling and plugging were found in the crossover duct that connected the RCS and CSC, and the upflow duct. Extended run times resulted in a blockage developing in the syngas cooler forcing the syngas to bypass a portion of the heat exchange area. The reduction in heat recovery lowered the plant electrical production by about 5%. Several modifications were made to the crossover/upflow duct and in the bottom of the RSC that eliminated plugging in the majority of the duct and reduced the rate of build-up in the remainder of the passage. After some final minor alterations in October 1988, the plant ran until the end of the programme on 23 January 1989 without any blockage occurring in the crossover duct. The post shut-down equipment inspections found no build-up of ash deposition in the duct. Although the operating period following the last improvement was not long enough to confirm that the problems of fouling and plugging were solved, better understanding of the problem and improved engineering design were obtained.

Dew point corrosion in the syngas cooler economiser occurred during operation on high-sulphur, high-chloride coals. The corrosion was stopped by increasing the operating temperature of the economiser. In addition, a few other small changes such as improvement to the configuration of the economiser section were made (McCarthy and Clark, nd; EPRI, 1990).

The lessons learned in the Cool Water Project provided a sound basis for the advancement of IGCC design.

5.2 Polk IGCC power plant

The Polk IGCC power plant in Tampa, Florida, USA is owned and operated by the Tampa Electric Company (TECO). The 250 MWe (net) IGCC demonstration plant has its roots in the 100 MWe Cool Water IGCC Project, and is one of two demonstrations of advanced IGCC technology in USA. It uses GE Energy's oxygen-blown, entrained flow gasifier, which began operation in 1996.

5.2.1 Syngas cooling system

The radiant and convective cooling concept was employed and many of the design requirements for the syngas cooling system came from the experience gained at Cool Water. The cooling system, as shown in Figure 21, was designed for full heat recovery originally consisting of a single RSC, two parallel horizontal fire tube CSCs and two raw gas heat exchangers (RGHE).

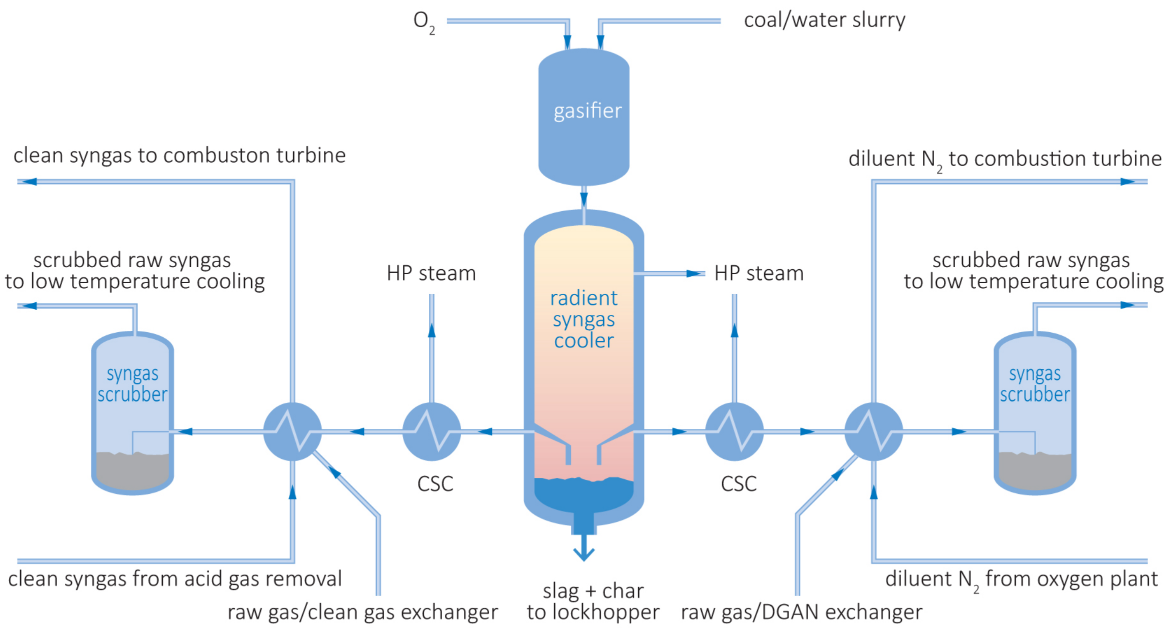

Figure 21 Original design of the syngas cooling system at the Polk IGCC power plant

The RSC consists of a membrane water wall with radial platen walls generating high pressure steam by cooling the hot syngas. Slurry with a solid coal/water ratio of 62–68% is injected along with O_2 into the gasifier, which typically operates at temperatures of 1260–1485°C (2300–2700°F) and 2.6 MPa pressure. The hot syngas produced in the gasifier passes first through the RSC located just below the gasifier and flows through the centre of a ring of tubes connected together in a configuration called a water wall. High pressure steam (11.4 MPa) is generated inside the tubes using circulating boiler feedwater. The water wall also serves to protect the RSC's pressure containing shell from the hot gas. The RSC is designed with sootblowing capability. The design exit temperature is 760°C (1400°F). The RSC typically recovers between 264 and 316 GJ/h (250 and 300 MBtu/h) of energy in the form of HP steam. This represents a recovery of between 12% and 15% of the coal's heating value.

The syngas passes over the surface of a pool of water located at the bottom of the RSC before exiting. The water pool collects virtually all of the slag and about half of the fly ash. The syngas with the remaining fly ash exits from the bottom of the RSC. Two RSC exits are provided and the gas flow is equally split between two water-cooled transfer ducts. The transfer ducts are sized to maintain a velocity of at least 26 m/sec. The specification also requires at least 20 pipe diameters of straight pipe downstream of each transfer duct inlet. The transfer duct configuration is that of a double pipe heat exchanger with the gas in the inner pipe. The annulus contains medium pressure circulating boiler feedwater, and hence some medium pressure steam (2.8 MPa) is generated.

A CSC is located at the end of each transfer duct. The gas flows through the tubes of CSC at relatively high velocity to improve the heat transfer coefficient. The CSCs use inlet ferrules to guide the inlet gas in order to minimise impingement and build-up of ash. By maintaining a minimum velocity of 30 m/sec in the tubes, the trade-off between particle fallout, deposit build-up, and tube erosion is also optimised. High pressure boiler feedwater circulates the shell side by natural convection, generating additional 11.4 MPa HP steam. The syngas leaves the CSCs at a temperature between 370–400°C (700–750°F). Together, the transfer ducts and CSCs recover an additional 3–4.5% of the coal's heating value. On leaving the CSCs, the syngas is sent through two RGHE, one for preheating clean syngas and the other for preheating diluent nitrogen for the combustion turbine.

The HP steam generated in the RSC and CSC is fed to the HP steam drum. From that drum, the steam flows to the HRSG in the power block. The RSC together with the CSCs produce about two-thirds of the IGCC system HP steam (McDaniel, 2002; Jenkins, 1994; TECO, 2004).

It should be pointed out that, in general, commercial gasification plants would only have one RSC exit duct. The Polk IGCC plant is unusual in having two RSC exits and two CSC. These originate from the original intention to demonstrate a hot gas desulphurisation process in a slip stream of the main plant. The CSCs are designed so that their outlet temperature provides gas at the proper inlet temperature for the hot gas cleaning unit (HGCU). The CSC on the raw gas/clean gas exchanger side would feed the HGCU system. This HGCU demonstration unit was never taken into service, but this feature has remained.

5.2.2 Operating experience

Over the five-year demonstration period from September 1996 to September 2001, TECO carried out a systematic campaign to address and resolve the usual technical issues. Since the demonstration, the plant has been in commercial operation.

Radiant syngas cooler

With exception of the failure of RSC seals, operation of the RSC was relatively trouble-free. RSC seals are at interfaces and water wall penetrations – gasifier refractory/water wall interface, steam/water header penetration in the 'roof', sootblower penetrations in the vertical/cylindrical section, and pressure equalisation passages for the water wall/shell annulus at the bottom of the RSC. All seals eventually failed due to either fabrication defects or design flaws, all of which were corrected.

The original RSC configuration had 122 nitrogen sootblowers to control the RSC outlet temperature. However, this vessel showed very little fouling and the sootblowers were rarely used. After several years and multiple feedstocks such as coal, petcoke and biomass, only four sootblowers had been required for normal operation and four more for nitrogen purging during start-up and shut-down. The unused sootblowers were removed in 2001. Despite not using the sootblower system, the RSC exit temperature remained consistently below 732°C (1350°F), lower than the designed value of 760°C (Dawson and others, 2008; TECO, 2004; McDaniel, 2002).

Raw gas heat exchangers

In the original design, RGHEs downstream of the CSC were incorporated to recover process heat by preheating clean gas and diluent N_2 going to the combustion turbine. In their first year of operation, the RGHEs experienced plugging and leaks resulting in seven forced outages and 139 days of plant downtime. Ash and slag fines that are not collected in the RSC sump built-up on the raw gas (tube) side of the RGHEs, resulting in plugging, corrosion, and eventual stress cracking of the RGHE tubes. The cracks led to leaks, resulting in ash particles being carried by the clean gas to the combustion turbine causing damage to the turbine blades. Since the RGHEs recovered less than 1.7% of the fuel's heat energy, the cost of repair and/or redesign of the RGHEs was not justified and therefore they were removed in mid-1997 (Dawson and others, 2008; McDaniel, 2002). Now the syngas leaving the CSCs goes directly to the wet scrubbers in the gas cleaning section.

Convective syngas coolers

The CSCs were subject to periodic plugging. After the removal of the RGHEs from service, fouling of the CSCs became a major cause of outage. Ash deposition occurred in the CSCs, particularly in the tubesheet inlet. The deposition rate was related to the fuel composition, operating condition and CSC geometry. The formation of deposits was often initiated during start-up and would continue to build and sometimes become detached and produce blockages of the inlet tubesheet. Significant geometric improvements such as modifications to the inlet gas flow path aided by the use of the Computational Fluid Dynamic modelling, combined with modifications to start up procedures, have greatly improved the situation. Although not eliminated, the problem of CSC pluggage is now deemed manageable (McDaniel, 2002; Barnes, 2013).

Corrosion problems were also experienced in the high-pressure particulate-laden syngas lines between the CSCs and the syngas scrubbers, predominantly at 90° elbows and branch connections. Corrosion at the transitions ultimately resulted in leaks leading to outages and downtimes. These problems were corrected by streamlining the piping, removing most of the elbows and internally coating the remaining ones with a special basaltic erosion resistant liner. The operating experience indicated that future plants could eliminate this problem by locating the syngas scrubber immediately adjacent to the final heat exchanger in the high temperature heat recovery area (Dawson and others, 2008; McDaniel, 2002).

5.3 Buggenum IGCC plant

Nuon Power's 253 MWe (net) IGCC power plant in Buggenum, The Netherlands, was first built as a demonstration plant for a test period of four years at the beginning of 1994. The plant was in commercial operation from 1998 until 2013 when it was decommissioned. The plant was designed for a wide range of imported coals. Later the plant operated with a substantial component of biomass (up to 30 wt% tested) in response to the Dutch government's renewable incentives.

Shell's SCGP gasifier with a gas quench and CSC cooling system as described in Section 4.1.2 is employed. The gasifier operates at 2.5 MPa pressure and a temperature of about 1600°C, with a gasifier outlet temperature of 1550–1600°C. At the outlet of the gasifier the raw syngas is quenched with recycled, cooled, particle-free syngas to a temperature of around 900°C. The syngas is then cooled to about 235°C in a water tube CSC by generating HP and IP steam. Particulate matter (mostly fly ash with a very small amount of unconverted carbon) is removed from the syngas first via a cyclone and then with a ceramic candle filter. The gasification section is completed by scrubbing the gas with water at about 165°C to remove ammonia and halides.

Both fouling and leakage of the syngas cooler occurred although the problems were minor. Until 2002 the Buggenum IGCC plant had had no influence on the coal procurement strategy. A large number of plant trips until this time could be attributed to uncontrolled changes in the quality of the coal. From 2002 the plant became responsible for its own coal procurement and this source of plant trip ceased. The fouling of the syngas cooler was mostly connected with the unannounced changes in coal quality. Improved operation such as increasing rapping frequency solved this problem. However, the fouling increased when the plant operated on some biomass (EPRI, 2006; Higman, 2007).

Leakages occurred in the water/steam system of the syngas cooler, caused by flaws in the mechanical design, resulting in repeated unplanned shut-down. The origin of the leaks lay in vibration and the lack of flexibility in the tube layout in the cooler. A redesign and refit of more flexible tube connectors have solved this problem (*see* Figure 22). Fly ash deposits have also blocked the top part of the syngas cooler several times. A study of the conditions for deposit formation led to better control of syngas temperature at the cooler inlet and this has prevented sintering of the fly ash during subsequent operation (Higman, 2007; Wolters, 2003; Barnes, 2013; Thattai and others, 2014).

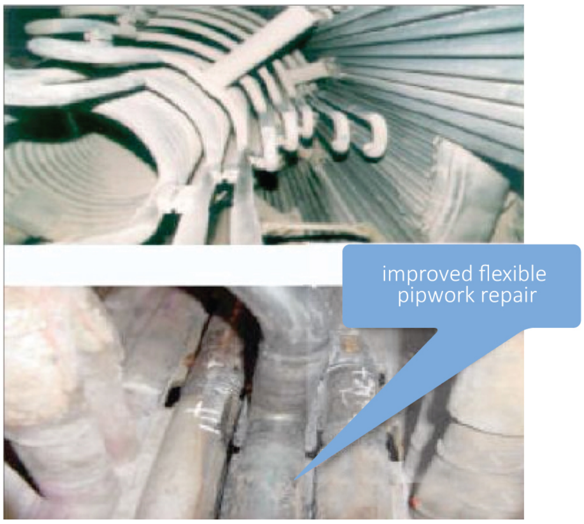

Figure 22 Improved flexibility for syngas cooler pipework repair at Buggenum

5.4 Puertollano IGCC plant

The 300 MWe (net) Puertollano IGCC power plant in Spain was launched as a demonstration project, supported by the European Union's Thermie program. The plant went into operation in December 1997 and the gas turbine was first operated on syngas in March 1998. The plant design was based on the concept of maximum integration of the three main units: gasification island, combined cycle and high pressure air separation unit. It was designed for a feedstock consisting of a 50:50 mixture of local, high-ash (about 40 wt%), low-sulphur coal and petcoke from the neighbouring oil refinery.

A PRENFLO gasifier with PSG cooling system (gas quench and CSCs, *see* Section 4.1.3) was adopted at the plant. The gasifier operates at a pressure of 2.5 MPa and a temperature between 1200 and 1600°C. The raw syngas leaving the gasification chamber at a temperature of around 1550°C enters the quench pipe where it is cooled with a flow of cooled, particle-free, recycled syngas to a temperature of about 800°C. The syngas is subsequently cooled to about 236°C in two water-tube syngas coolers, which generate saturated steam. The HP boiler is integrated into the gasifier, whereas the IP boiler is in a separate vessel (*see* Figure 14 on page 35).

During the first five years of operation, fouling of the CSCs occurred resulting in some unplanned outages. Two primary mechanisms for CSC fouling were identified. The first was the presence of 'sticky' ash caused by condensation of metal sulphide compounds on the heat exchange surface upon cooling. This type of fly ash had melting temperatures between 400°C and 800°C and could not be easily removed due to its adhesive and sticky properties, which was found to be an operational issue. However, reducing the gas inlet temperature to cooling surfaces from designed 800°C to around 700°C by increasing the quench gas flow solved this problem. The second mechanism, blockage by 'fluffy' fly ash was attributed to a too-conservative approach to gas velocities in the design. Cleaning the surface using the rappers installed was not effective due to the fluffy nature of the fly ash. This problem was alleviated by increasing the velocity of the syngas flow to approximately 10 m/s (*see* Figure 23). The operators suggested that future designs should consider reduction of the size and heat exchange surface area of the IP boiler in order to mitigate ash deposition and plugging problem. The cleaning of the CSCs was performed by rappers that had to be changed every year. Better materials should be selected for rappers and plates. In recent years, the operation of syngas cooler suffered high vibrations in quench gas compressor, water leakages at IP economiser and flooding in the quench gas compressor aspiration pipe. Water leakages at the IP economiser were caused by mechanisms including corrosion, erosion-corrosion and mechanical fatigue. Standby corrosion is another important mechanism for such leakages and this can be prevented by keeping all equipment surfaces free from contact with moist air or water containing dissolved oxygen by, for instance, purging the system with nitrogen. Flooding in the quench gas compressor occurred once and was due to downtime corrosion resulting in a water leakage that was not detected until the gasifier was started up (Coca-Llano, 2015; ELCOGAS S.A., 2014; Peña, 2012; Alarcón, 2012; Barnes, 2013). These problems can be prevented by optimise the operating procedures.

Figure 23 FCSC fouling – before and after remedial measures (Alarcón, 2012)

5.5 Wabash River Coal Gasification Repowering Project

The 262 MWe (net) Wabash River Project is the first of the US DOE supported IGCC power plants. It started operation in November 1995 and the demonstration period lasted until December 1999. The plant was originally designed to use a range of local coals with a maximum sulphur content of 5.9% (dry basis). In addition, petcoke and blends of coal and petcoke were tested at the facility. It is currently using petcoke as feedstock.

The gasification process used at Wabash River is the E-Gas technology featuring an oxygen blown, slurry feed, and refractory lined two-stage entrained flow gasifier with continuous slag removal (*see* Section 4.1.4). A 60/40 wt% coal/water slurry is combined with O_2 (95% purity) and injected into the gasifier. The gasifier operates at 2.76 MPa (400 psig) and a temperature of about 1371°C (2500°F) in the first stage. The coal undergoes partial combustion, releasing heat that causes the gasification reactions to proceed very rapidly and the ash to melt and flow down to the bottom of the gasifier. The raw syngas flows upward into the second stage where it reacts with added slurry. The coal devolatilises, pyrolyses and partly gasifies by reaction with steam. Evaporation of water in the slurry and the endothermic chemical reactions cause the temperature of the raw syngas to be reduced to about 1038°C (1900°F). The syngas is further cooled in a fire-tube CSC producing high pressure (11 MPa) saturated steam (Wabash River Coal Gasification Project Joint Venture/DOE, 2000).

Ash deposition in the CSC and associated equipment was a big concern during the early operation. Thermal cycles of the hot gas path were a leading contributor to CSC plugging due to spalling of ash deposits in upstream equipment and piping. Ash deposits formed on the walls of the second stage gasifier and piping systems that connect the gasifier and CSC. As the deposit mass increased, either system differential pressure increased or deposits broke free and plugged downstream lines or the CSC tubes, forcing the plant off line. Downtime in the first two years from ash-related problems totalled more than 47 days. Sometimes deposits also formed within the CSC tubing. Solids accumulation at the tubesheet caused tube plugging (*see* Figure 24) and high differential pressures. At some point, the solids-laden gas through the open tubes reached a velocity high enough to cause erosion. Study of the ash deposits and formation patterns combined with computational fluid dynamic modelling provided an understanding of ash behaviour that suggested three solutions: first, the refractory of the second stage reactor was replaced with material that did not form tenacious bonds with the ash. Second, the piping system was replaced to eliminate high velocity impact zones where ash deposits preferentially formed. Third, a screen was installed at the inlet to the CSC to prevent large particles from reaching the tubesheet. Since installation of these modifications in 1997, downtime caused by ash deposition has been eliminated (Wabash River Energy/US DOE, 2000).

Figure 24 Fouling and plugging of the CSC tubes at the Wabash River (Keeler, 2003)

Exposure to moisture during downtime tends to concentrate chlorides and other corrosion products at the scale metal interface that can subsequently cause the chromium oxide rich scales to spall from the tubes. This process has been suggested as the cause of accelerated corrosion rather than aqueous corrosion during downtime. The presence of sulphides in the scales is suspected as enhancing downtime dew point corrosion. Therefore, measures (for example purging with nitrogen) are taken to avoid the conditions that could lead to downtime corrosion (Barnes, 2013; Wabash River Energy/US DOE, 2000).

Fouling of the boiler tubes increases the temperature of the downstream filter elements in the particulate removal system. The higher temperature accelerates corrosion and increases the blinding rate of the elements. Operating conditions were optimised to minimise the fouling rate and new methods of cleaning the tubes were incorporated into the maintenance programme allowing operations to come back online with an outlet temperature close to design, thus restoring the CSC to design heat transfer conditions after outages. However, the CSC needed frequent cleaning (syngas cooler cleanout was carried out on a 10-15 week cycle) and remained one of the leading causes of downtime during more recent commercial operations (Wabash River Energy/US DOE, 2000; Payonk, 2008).

5.6 Nakoso IGCC demonstration plant

The Nakoso IGCC plant in Japan is a 250 MWe (gross) IGCC demonstration project that started operation in September 2007. The Nakoso IGCC plant utilises MHI's air-blown, dry-feed, pressurised, two-stage, entrained flow gasification technology. The basic design concepts of the MHI's gasification and high temperature cooling system (*see* Figure 16) are similar to those of E-Gas technology used in Wabash River and are described in Section 4.1.5. A series of tests were conducted over a period of about five and a half years until March 2013 since when the plant has been in commercial operation.

Various types of coal (bituminous and subbituminous) from around the world were tested at Nakoso. The demonstration operation has been successful, achieving all initial targets including reaching 2238 continuous operating hours and completion of a 5013-hour durability test without any serious damage being found. During the demonstration operations, several incidents occurred that forced the plant off line. These problems occurred mostly during the 5000-hours durability test; they were mainly experienced by the auxiliary facilities and not in the main facilities such as the gasifier. The causes of the problems were identified and remedial measures were taken that have solved the problems. The raw syngas contained a small amount of particulate matter that resulted in erosion of syngas tubes in areas such as the base of thermowell and pipe bends despite the fact that pipe bends used erosion-resistant material. Erosion prevention measures should be incorporated in future plant design (Ishibashi, 2013; Asano, 2012; Watanabe, 2010, 2012). No operating difficulties associated with the high temperature syngas cooling system have been reported.

It should be mentioned that the IGCC plant was in operation when the earthquake took place in 2011. The system was shut down automatically and safely, triggered by the detection of high vibration at the turbine, which proved the reliability of the system in an unanticipated way. A tsunami followed the earthquake, and almost all equipment on the ground was submerged by seawater and suffered serious damage. In spite of amplified damage with aftershocks a month later, the IGCC plant was restored to operation within 4.5 months and has since been in stable operation (Ishibashi, 2013; Nunokawa and Asano, 2014).

5.7 Zao Zhuang (ZZ) Plant

ZZ plant in Zao Zhuang City, Shandong Province (China) is a 96% SES (Synthesis Energy Systems, Inc) owned joint venture with Shandong Hai Hua Coal & Chemical Company Limited. The ZZ plant consists of two gasification trains designed to process 400 t/d of coal middlings (washery wastes) with up to 40 wt% ash. Each gasifier has a capacity to produce 14000 m^3/h of syngas. Clean syngas produced at ZZ plant is sold to a neighbouring plant for methanol production. The U-Gas gasification technology developed by Gas Technology Institute (GTI) is used at ZZ plant. SES has a worldwide exclusive license for GTI's U-Gas technology.

The U-Gas process has a single-stage, fluidised bed gasifier with a dry-feed system. Oxygen, oxygen-enriched air, or air is injected together with steam into the reactor that operates under a bubbling bed fluidisation regime. The reaction temperature is controlled to maintain high carbon conversion and non-slagging conditions. Figure 25 shows a typical U-Gas gasification process. The hot, raw syngas exiting the gasifier passes through a series of cyclones to remove particulate matter in the syngas. It then enters a CSC for cooling and heat recovery. HP steam generated by the CSC that is not used by the gasification process is exported to meet other plant needs. Cooled syngas leaving the CSC is sent to downstream gas cleaning systems.

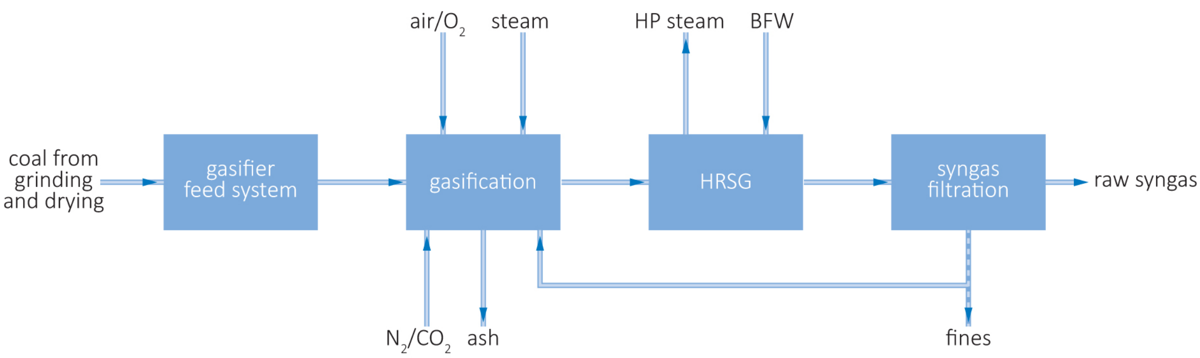

Figure 25 Flow sheet of a U-Gas gasification process (Khan and Lau, 2012)

ZZ plant started commercial operation in 2008. During the first year of commercial operations, the plant achieved over 98% availability of single gasifier capacity using low grade, high ash coal and coal washings. Despite being a commercial plant, a series of tests were carried out at ZZ plant. A wide range of coal, coke, waste and biomass have been tested here. Coals tested include peat, lignite, subbituminous and bituminous, and waste coals from around the world. Test results show that the U-Gas process is well suited to gasify low grade, high ash coal and coal waste, and can achieve over 82% cold gas efficiency and greater than 98% carbon conversion. During the first years of operation at ZZ plant, SES devised and implemented multiple improvements to the U-Gas technology that led to increased carbon conversion, overall gasifier efficiency, operability and heat recovery. Many of these improvements were included in the design of the Yima methanol production plant. The Yima plant came into service in 2012 and has three U-Gas gasifiers. The gasifiers operate at 1 MPa and each with a capability to produce 45000 m^3/h of syngas. Both ZZ and Yima plants are in commercial operation (Khan and Lau, 2012; Lalou, 2014).

6 Concluding remarks

High temperature syngas can be cooled using a radiant cooler (RSC), convective cooler (CSC), direct quench cooler or any combination of these coolers. A RSC works at high temperature (>700°C) and uses radiant heat transfer to cool the hot syngas. Heat is recovered by generating HP steam. RSC has the tube arrangement similar to that of cylindrical fired boilers where cage shaped tube panels are used. CSC is usually shell and tube type heat exchanger/boiler consisting of a set of tubes in a container. Heat is transferred by convection and conduction. Both fire tube boiler and water tube boiler design have been used for CSC. HP and/or IP steam are generated by CSC. In a direct quench cooler, the hot raw syngas is rapidly cooled by injection of cooling medium into the syngas. There are three different direct quenching techniques: water quench, gas quench and chemical quench. The water quench and gas quench use water and syngas, respectively, as cooling medium. In chemical quench cooling, the syngas is cooled while the thermal energy is used to produce other valuable products.

RSC is only used for very high temperature operation and therefore it is usually applied to entrained flow gasifiers that operate under slagging conditions and produce syngas with temperatures significantly higher than 1000°C. CSC is generally used to recover heat from coal-derived syngas with temperatures of 1000°C or lower. There is no heat recovery in water and gas quenching process.

In general, syngas leaves a gasifier at temperatures in the range of 400°C and 1600°C. The temperature of the cooled syngas is determined by the operating temperature of the gas cleaning process immediately downstream of the syngas cooler. It is common that a syngas cooling system combines different types of syngas coolers. Various syngas cooling systems are in operation in existing IGCC plants.

Radiant and convective cooling

This design is suitable for cooling hot syngas with temperatures substantially higher than 900°C. The hot syngas from the gasifier enters a RSC in which it is cooled to a temperature of approximately 800°C and then flows into CSC for further cooling to desired temperature.

GE Energy has adopted this design as one of the three cooling concepts (radiant and convective cooling, radiant and quench cooling and total quench cooling) in its slurry feed, downflow, entrained flow gasification process and has successfully demonstrated this design concept in Cool Water and Polk IGCC plant. The operating experiences at the two plants show that the operation of RSC is generally smooth and almost trouble free after the early design and fabrication defects were corrected. Plugging occurred in CSC and crossover duct that connects the RSC and CSC and the problems were mitigated by geometric changes.

Radiant and quench cooling

This design uses a RSC followed by a water quench cooler. Either a full or a partial quench cooler can be used after the RSC. GE Energy developed a radiant and water quench cooling design in which the syngas is firstly cooled in a RSC to approximately 800°C. The syngas then flows through the quench chamber that is located underneath the RSC in the same vessel and is cooled to around 200–220°C. GE Energy applied this design to the Edwardsport IGCC plant. Due to various operational issues, as of January 2015, the Edwardsport IGCC plant has been operating on natural gas rather than coal since its commercial operation started in 2013. Therefore, no operating experience of the syngas cooling system is reported by the operators.

Siemens has been developing its own radiant and quench cooling design for the Siemens Fuel Gasification (SFG) process.

Partial quench and convective cooling

In this design, the hot raw syngas is firstly quench cooled to a temperature well below the ash melting point of the coal, and is then cooled in a CSC. Both Shell's SCGP and Uhde's PREFLO gasification process employ the gas quench and CSC cooling concept although design details are different. The syngas leaving the gasifier is cooled to a temperature of 800–900°C by mixing directly with cooled, dust-free recycled syngas of about 230–250°C. The syngas exiting the quench cooler is further cooled to the desired temperature in CSC. Shell's cooling system design was demonstrated in the Buggenum IGCC plant (closed in 2013) in The Netherlands, whilst the Uhde's syngas cooling concept has been demonstrated at Puertollano IGCC plant in Spain. Operations at the two plants provided useful lessons for improvement and optimisation of the design and operating conditions of the partial quench and convective syngas cooling system.

Entrained-flow, two-stage gasifiers employ chemical quenching in the second-stage gasification. The sensible heat in the syngas leaving the first stage of the gasifier is used in the endothermic gasification reactions in the second-stage of gasifier. The syngas exits the gasifier at temperatures of 1000–1100°C and enters the CSC for cooling and heat recovery. E-Gas, MHI and EAGLE gasifiers are examples of the entrained-flow, two-stage gasifier with differences in design details. E-Gas and MHI gasification processes are in commercial operation in Wabash River IGCC (USA) and Nakoso IGCC plant (Japan), respectively. No major issues regarding the syngas cooling systems have been experienced in commercial operations of the plants.

Total quench cooling

In total quench cooling, water is sprayed into the quench chamber to cool the hot syngas. There is no heat recovery in this design and the raw gas exiting the quench cooler is saturated with moisture. This is one of the three cooling concepts adopted by GE Energy. Total water quench cooling is a mature technology and it is widely used in gasification plants for production of chemicals. Shell recently developed a coal gasifier with a bottom water quench cooling system.

Total quench cooling is reliable and has low capital cost but also results in low overall process efficiency.

CSC only design

The fluidised bed gasifiers operate at relatively low temperature (900–1100°C) that is high enough to decompose most of the tar, oils, phenols, and other liquid by-products but lower than the ash fusion temperature so as to avoid clinker formation. The syngas leaving the gasifier has a temperature of ~1000°C and is usually cooled in a CSC. CSC with either water tube or fire tube boiler design can be used. Due to the non-slagging conditions used by fluidised bed gasifiers, fouling of CSC should be minor. With optimised design and operating conditions, dust deposition and/or caking, erosion and corrosion in the CSC can be minimised. Several chemical plants in China operate U-Gas gasifiers (a type of bubbling fluidised bed gasifier) using CSC for high temperature syngas cooling. This gasification process has been successfully operated on a wide range of fuels including low grade coal and waste coal.

The selection and design of a syngas cooling and heat recovery system have to consider the characteristics of the coal feed and syngas produced, the type of gasifier used, the overall gasification process application and, of course, the costs. The syngas cooler is often one of the most expensive items in a coal gasification plant. The radiant and convective cooling design can achieve maximum heat recovery from syngas and hence the highest potential overall process efficiency. However, the investment cost is significantly higher than the other cooling system designs. A RSC is an expensive and bulky piece of equipment that only works at high temperature. CSC is capable of effectively cooling and recovering heat from syngas with relatively low temperatures ranged from 300°C to 900°C. It also has a smaller footprint than a RSC and has been employed in various gasification processes. However, compared to RSC and quench coolers, convective coolers have a higher risk of fouling and plugging which can cause plant outages and high pressure losses leading to increased downtime and higher maintenance costs.

A total quench cooling system is least energy efficient but has significantly lower capital cost. When CO_2 capture is required, the total quench design has an advantage as the syngas contains a high water content that is required by the CO shift reaction. Water quench cooling consumes large quantities of water and requires complex waste water treatment. Other problems associated with total quench design include discharge water permitting issues, added operating/maintenance costs and operating problems due to increased water treatment facilities.

Experiences with operating the commercial IGCC plants worldwide, especially the IGCC demonstration plants, has shown that the syngas cooling system design concepts described above are sound. Lessons learned from the operations will help to improve and optimise the designs and operating conditions leading to more efficient, more reliable syngas cooling and heat recovery systems.

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