Chapter 1

Considerations for the Design and Operation of Pilot-Scale Coal Gasifiers

Yongseung Yun, Seung Jong Lee and Seok Woo Chung

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/49951

1. Introduction

Although there are many successful commercial coal gasifiers, the basic form and concept have not been improved for the last 20 years or so. Details on the design and operation for the commercial coal gasifiers are closely guarded as proprietary information. Considering the recent technology jump in CFD and monitoring systems, at least some coal gasifiers should come out as a more revolutionary style. Especially it's important to test the novel gasifier types when the gasification has widened the application scope in environmental and biomass areas. Many research ideas should have a chance to design and test in the more realistic conditions of high pressure and high temperature with molten slags. This chapter wants to give an introduction and practical considerations to design and operate the bench scale to pilot scale gasifiers at the actual coal gasification conditions.

The chapter consists of following sections. Each part will give a practical view point to build and test the gasifier at the actual gasification conditions, which are toxic and explosion-prone when the syngas is not trapped inside the gasifier. The scope of the chapter will be focused on the pilot-scale size since the purpose is to focus on the wide distribution of information on the coal gasifiers as well as to stimulate the more active involvement of research groups on the future coal gasifier development.

Key items are, currently known types of coal gasifiers, selection guidelines of coal gasifiers, comparison of slurry type vs. dry type gasifiers, and the discussion regarding the operating pressures and manufacturing limits, etc. Another aspects are the difference in slagging gasifiers and partial/non-slagging gasifiers, coal selection guidelines for gasification, application of CFD for the gasifier design, coal feeding methods, and in-situ estimation of gasification status inside the gasifier.

Other points are the choice in gasifier wall (refractory, membrane wall), slagging/fouling related problems, and finally the future direction of coal gasifiers.

Institute for Advanced Engineering (IAE) has worked in the pilot scale coal gasifiers from 1994. Figures 1-3 demonstrate the coal gasifiers of 1-3 ton/day scale at the operation range of 3-28 bar, 1,300-1,600°C [1-3]. Figure 1 shows two slagging coal gasifiers of 3 ton/day capacity. Left side gasifier was built in 1994 and operated since at the maximum pressure of 28 bar and 1,400-1,550°C. Right-hand side gasifier was mainly applied to the waste oil gasification and used as a test bed for the top-feeding coal gasifier.

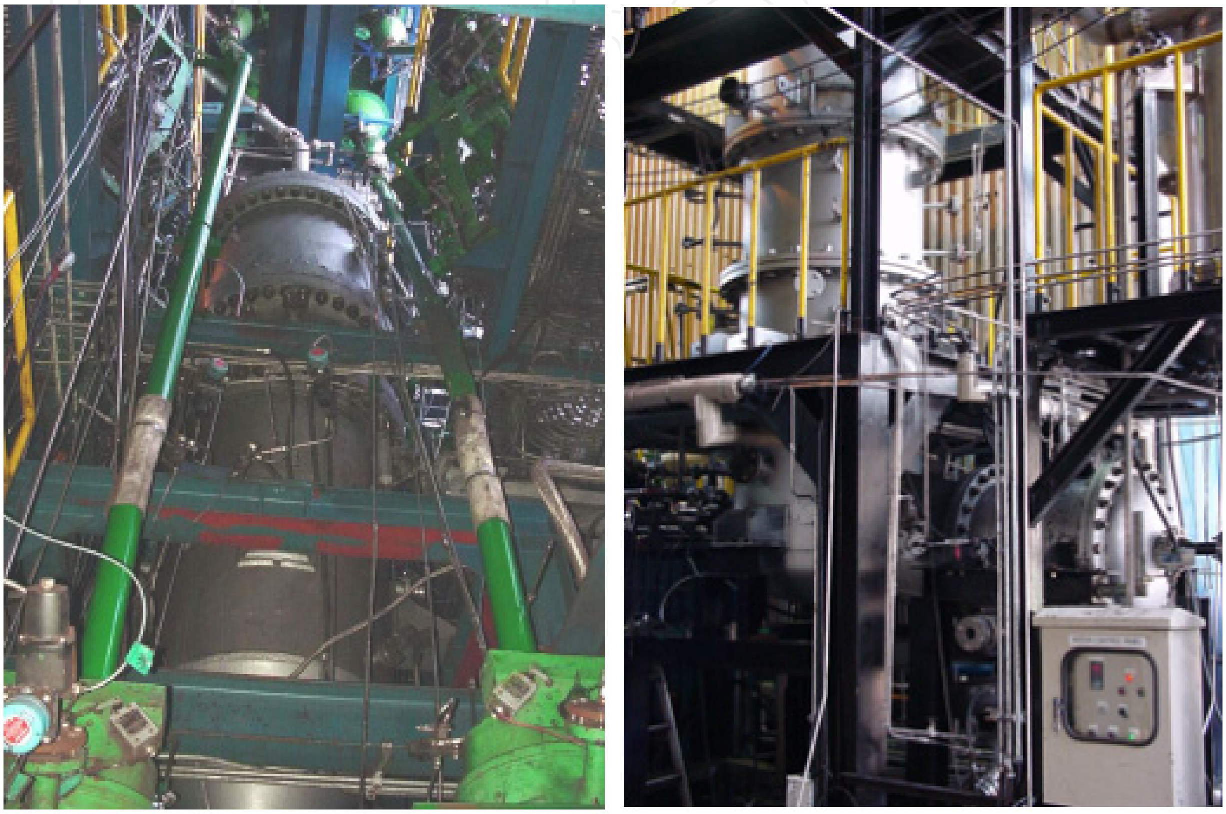

Figure 1. Pilot-scale coal gasifiers of slagging type (Left: side-feeding/max. 28 bar, Right: top-feeding/max. 5 bar)

Figure 2 shows the 2 ton/day pilot-scale coal gasifier which chose the top-feeding, partial/non-slagging entrained-bed type and normally operated at 20 bar, 1,300-1,450°C range. Another type of gasifier which chose the membrane wall, top-feeding, slagging type is shown in Figure 3. Idea of applying membrane wall with a layer of refractory was applied to make a gasifier as small as possible.

2. Selection guidelines of coal gasifiers

History of coal gasification starts from early 20th century, but the real commercial size of gasifiers can be supplied from limited vendors. Table 1 shows the commercially available coal gasifiers that can treat coal over 1,500 ton/day. To reach this size of gasifiers, 3-4 steps of development are necessary: bench scale, 10-30 ton/day, 200-500 ton/day, and finally the 1,500-3,000 ton/day commercial size. Pilot coal gasifiers typically include bench to 30 ton/day scale.

Figure 2. Pilot-scale coal gasifier of top-feeding, partial/non-slagging entrained-bed type (max. 21 bar)

Figure 3. Pilot-scale coal gasifier of membrane wall, top-feeding, slagging type (max. 21 bar)

Key factors in deciding the suitable gasifier type will be discussed in this section. As shown in Table 1, currently known coal gasifiers can be classified with choices on the reactor type which will decide the residence time in gasifier, coal feeding method and location, gasifier stages and number of burner nozzles to supply reactants, gasifier wall type in protecting the metal gasifier wall, whether coal ash will be converted to slag or just fly-ash, and the oxidant whether to use oxygen or air.

Item	Shell	Uhde	Conoco-Phillips	Siemens	GE Energy	MHI	OMB	Lurgi
Country	Netherlands	Germany	USA	Germany	USA	Japan	China	Germany
Reactor Type	Entrained	Entrained	Entrained	Entrained	Entrained	Entrained	Entrained	Fixed
Feeding	Dry/Side	Dry/Side	Slurry/ Side	Dry/Top	Slurry/ Top	Dry/Side	Dry/Side	Dry/ Top
Stages	1	1	2	1	1	2	1	1
Wall	Membrane	Membrane	Refractory	Membrane	Refractory	Membrane	Membrane	-
Slagging	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Oxidant	O_2	O_2	O_2	O_2	O_2	Air	O_2	Air/O_2
Burners	4	4	2+1	1	1	4+4	4	-

Table 1. Currently available commercial coal gasifiers

First of all, most important remark will be that there is no universal coal gasifier to meet all the different technical requirements. Each gasifier has developed to meet the specific needs from the customers and should see where the preferred gasifier type has the most proven experience in the industry. One of the most frequently asked question is that a specific gasifier can be utilized interchangeably both for the power generation and for the chemical production. If the plant size is small, this option might be possible with limited option. But most commercial gasification plants usually cost 10-200 million US$. With this high capital cost, the gasifier which is the core part of the plant should be designed to maximize the wanted final product with highest efficiency, along with minimum maintenance and without any accident.

Item	Option
Reactor type	Entrained, Fluidized, Fixed(Moving-bed)
Coal feeding	Dry, Wet(Slurry)
Feeding location	Top, Side
Gasifier wall	Refractory, Membrane wall
Ash treatment	Slagging, Non-slagging
Gasifier pressure	High. Medium, Atmospheric
Oxidizing agent	Oxygen, Enriched oxygen, Air
Syngas cooling	Quench, Radiant/Convective cooling
Gasifier stages	One, Two
Burner number	One, Multi

Table 2. Selection Items and Option for Coal Gasifier

2.1. Entrained-bed vs. fluidized-bed vs. fixed-bed

Currently available gasifiers can be classified basically as three reactor types. The processes that require a high throughput capacity in a single reactor generally employ entrained-bed type, as in IGCC, since the reactor size can be minimized by fast residence time (typically less than 5 sec) in the gasifier as well as by high pressure. Although large scale operation by entrained-bed type has successfully demonstrated and employed commercially, the experience is not long enough as fixed or fluidized-bed gasifiers. Also most prominent disadvantage of entrained-bed gasifier is in its high capital cost involved due to condensed configuration of parts.

Fluidized-bed has been developed basically for the application to low-grade fuels or feedstock, like a low-grade coal and wastes that contain various materials. After two oil shocks in the 1970's, many companies were interested in using low grade fuels which were not an interested material, mainly it was coal. Operating principle of fluidized bed involves even distribution of oxidizing agent through the distribution plate in bubbling type, or through the reactor in circulating type. Gas bubbles tend to flow via the less congested area, in turn result in dead zone inside the reactor. This causes the difficulty in scale-up design and operation. Most prominent fluidized-bed examples are FBC boiler and waste pyrolysis plants.

Fixed-bed has a long history of industrial experience as a so-called Lurgi type, which is still used in a large number in China. Due to its long industrial experience, it's reliable. But it's not suitable for the single large scale gasifier. Lurgi recently has achieved to make a gasifier of 1,600 ton/day capacity.

Item	Entrained-bed	Fluidized-bed	Fixed-bed
Residence time in reactor	3-5 sec	minutes	>30 min
Single unit size	Medium-Very large	Medium	Medium
Pressurized reactor	Easy	Not-easy	Not-easy
Complexity	Complex	Complex	Simple
Coal particle size	< 100 microns	6-10 mm	6-50 mm
Coal range	All ranks	Limit in agglomerating coals	Limit in agglomerating coals
Oxygen consumption (O_2/coal ratio)	Large (0.9-1.0)	Medium	Low (0.7-0.8)
Tar formation	None or Very little	Small	Many
Industrial experience	From 1980's	From 1970's	From 1930's
Advantages	Large scale operation	Suitable for low grade fuels	Reliable
Disadvantages	Expensive	Difficult in scale-up, Not suitable for fines	Limit in size

Table 3. Comparison of typical three gasifier types

2.2. Dry feeding vs. slurry feeding

Dry feeding gasifiers were developed mainly in Europe, while the gasifiers that had been developed in United States were slurry-feeding type. Table 4 summarized the key differences of dry and slurry feeding systems.

Maximum carbon conversion in the single-pass gasification without char-recycling could be obtained from the high-reactivity coals. The actual gasifier operation yielded nearly 100% carbon conversion for the high-reactivity coals. In general, dry-feeding entrained-bed gasifier can treat all ranks of coal while the slurry-feeding entrained-bed gasifier is suitable for bituminous coals of higher rank. However, unless the gasifier is designed to cover all different reactivity of coal in the reaction, even for the dry-feeding gasifier, low carbon conversion would result if the gasifier volume were not sufficient to sustain enough residence time of coal powder. In this case, the char-recycling process is required.

Item	Dry-feeding	Slurry-feeding
Coal type	All ranks	Not suitable for high moisture-containing low-rank coals
Efficiency	high	moderate
Carbon conversion	>99%	>99%
Capital cost	high	Moderate
Typical gasifier wall type	Membrane wall	Refractory
Cold gas efficiency	High	Moderate
Typical max. gasifier pressure	45 bar	80 bar
Key application area	Electricity generation	Chemical production
Commercial gasifiers	Shell, Uhde, Siemens, MHI	GE energy, Conoco-Phillips

Table 4. Comparison of dry and wet (slurry) feeding type gasifiers

Maximum gasifier pressure is limited to about 45 bar in the dry-feeding gasifier and to about 80 bar for the slurry feeding system. The bottleneck of the maximum available gasifier pressure is in the coal powder feeding system for the dry feeding type and in the economically manufacturable pressure vessel of large size which is more than few meters diameter in commercial applications.

2.3. Gasifier stages

Most coal gasifiers employ a single stage which is simple in design and less expensive with respect to manufacturing pressure vessel. When the feed coal is relatively uniform in quality and in other properties, the residence time inside the gasifier will be constant in theory if the constant feeding is guaranteed. When the coal and oxygen feeding is uniform, all the times, the performance of the gasifier will be satisfactory, although there would be some mechanical or components related problems. This point will be crucial in designing and operating the pilot coal gasifier. The most important factor in operating coal gasifiers should be the constant feeding of coal powder. Feeding of oxygen and steam is relatively easy since there are in gas states.

Unfortunately, coal is becoming more and more heterogeneous and lower quality. In many plants, feed coals are mixed from widely different origins. In this case, particle residence time inside the gasifer might not sufficient to guarantee the full conversion of all the input coals. Low reactivity or larger size coal particles that are contained in the input feed coal would pass through the gasifier without fully reacting.

Two stage design is introduced to accommodate the heterogeneous coal particles in a single reactor. Feeding amount of coal and oxygen can be manipulated in two separate positions at the gasifier. By adjusting the feeding amounts, hot local temperature is possible in the gasifier that will gasify even the least reactive particles coming with the coal feed. If the slagging is required, the temperature zone that is enough to melt all the inorganics should exist inside the gasifier.

One thing should be noted here. If one single pass through the gasifier is not sufficient to convert all organic components to syngas, unreacted char can be collected and recycled to make a carbon conversion above 99%. But recycling usually incorporates expensive additional feeding systems. If possible, it is the best to make a gasifier to fulfill 100% carbon conversion in a single pass through the gasifier.

2.4. Top-feeding vs. side feeding

Gasification produces gas and solid products as syngas and slag/fly-ash. Gas naturally tends to move upward and solid moves downward by gravity. If the properties of gas and solid apply just as they are, side feeding would be most natural. But side feeding produces operational problems in the areas of slag tap as well as in the syngas outlet which is located at the top section of the gasifier. In addition, slag temperature should be monitored and maintained at high enough temperature to ensure the smooth flow of molten slag.

Top feeding is injecting coal and oxygen, steam from the top side of the gasifier at the velocity above 20 m/s. Typical commercial top feeding coal gasifiers have a L/D ratio of about 1.5, in that the gasification flame might reach the slag tap area and can maintain the smooth passage of molten slag or ash with the fast flowing hot syngas through the slag tap. If the L/D ratio is higher than 2, careful arrangement to maintain the slag tap temperature should be employed like a slag tap burner.

Item	Top-feeding	Side-feeding
Advantages	Simple design (usually one feed nozzle)	Separate gas and solid flow direction
Disadvantages	Entrainment of fines	Complex design (2-12 feed nozzles)

Item	Top-feeding	Side-feeding
Main problem area	Nozzle erosion (Short life span)	Slag-tap plugging, Syngas exit line plugging
Design aspect	Simple	Complex

Table 5. Comparison of top-feeding and side-feeding methods

2.5. Refractory vs. membrane wall

Entrained-bed gasifiers run at 1,300-1,600^{o}C, which requires a certain way of protecting the metal wall in the gasifier vessel. There are two ways to protect the vessel metal wall: by refractory or by membrane wall. Sometimes water jacket is used, but still requires the refractory protection.

Simply put, refractory system is cheap but bulky and heavy while the membrane wall is expensive and requires a good manufacturing skill. For the small pilot coal gasifier, using refractory of high chromium content (20-60%) is the cheapest way. Large gasifiers are using the brick refractory, but the pilot scale gasifier employs the mixture of refractory powder and water to fill the mold of the gasifier.

Refractory system is heavy and requires a long time (more than one day) of pre-heating before the gasification run. Membrane wall system is like an engine that is quick to ignite and run.

2.6. Slagging vs. non-slagging

Inorganics in coal should be treated to become a harmless material. Slagging gasifier converts inorganic parts to slag that is made by treating ash at the temperature above the ash fusion temperature. Non-slagging gasifier transforms the inorganics to ash form that is sometimes causing heavy metal leaching problem.

Ash that is made in the typical coal combustors like in coal fired boilers might leach heavy metals when stored outside. But, the intertwined structure in slag that is made during the melting in the gasifier prevents the heavy metals to come out at the normal environmental conditions unless the slag is meted again at high temperature above the melting temperature. In theory, slag should be the target to obtain, rather than ash that might cause a secondary environmental problem by heavy metal leaching.

But the problem is that utilization of slag is quite limited in current market although it is environmentally more benign, while fly-ash has many customers who want to buy. Slag can be used as a construction material or supplement for construction bricks, but the utilization record is not so bright. Fly-ash from the combustion processes has a well proven record in use during the last 5-8 years as cement fillers. When the fly-ash contains less than 5% carbon (preferably less than 3%), the ash is widely used as a supplement of cement filler.

Conventional non-slagging gasifiers adopt fluidized-bed type of reactor. Recent reports indicate that entrained-bed type of non-slagging gasifier might provide the advantages of fast reaction and the utilization of inorganics as a fly-ash form, or use the collected fly-ash as a low-grade fuel.

Item	Slagging	Non-slagging
Gasifier temperature	1,400-1,600°C	Less than 1,450°C (entrained-bed) 850-950°C (fluidized-bed)
Final type of inorganics(ash)	Slag	Ash
Utilization of slag/ash	Still not well accepted in industry	Well proven as cement filler

Table 6. Comparison of slagging and non-slagging types

Figure 4. Slag(left) from slagging gasifier and fly-ash(right) from non-slagging gasifier

2.7. Gasifier pressure

In the case of IGCC, gasifier pressure is typically determined by the gas turbine compressing pressure requirement. Operating pressure of commercial coal gasifiers are in the range of 22-28 bar in the IGCC plant using 7FA gas turbine. The 1.5th generation IGCC where using 7FB gas turbine requires a gasifier pressure at 41 bar to fulfill the inlet gas pressure for the 7FB machine. Higher gasifier pressure can push the gas turbine blades more strongly and thus can produce more power.

When the final product is chemical intermediates that should be used in the ensuing high pressure conversion process, high pressure operation is all the times more economical than the atmospheric or low pressure operation and the following syngas compression. Gas compression is one of the expensive processes and requires a heavy maintenance.

If the pressure of the chemical conversion process that is using the syngas from the coal gasifier requires higher than 50 bar, practically slurry feeding system is preferred over the dry-feeding. Dry feeding of coal powder above 50 bar is not practical by the currently available technologies till now.

Some people argue that the gasification pressure gives a profound variation in syngas composition. Gasification reaction itself would be dependent upon the pressure by thermodynamic principles. But in reality commercial gasifiers convert all carbon and hydrogen in coal to CO and H_2 at the optimal operating condition, and more H_2 is produced when steam is more added or slurry feeding is employed. If one pass of coal through the gasifier cannot reach >99% carbon conversion, the char or fines will be recycled to achieve the necessary conversion. Therefore when the gasifier is operating at the optimal condition which means that proper amount of oxygen and steam are supplied for more than 99% carbon conversion at all times, the gasifier pressure would not significantly influence the final syngas composition that will be used as a raw gas for power generation or manufacturing chemicals.

2.8. Oxidizing agent

In gasification, using oxygen is like driving a luxurious sports car whereas using air is like driving a small compact car. Pure oxygen pushes the gasification reaction with real fast response, while using air for the gasification responses rather slowly. Applying oxygen requires a heavy initial investment (notably ASU(air separation unit)) to gain fast response in controlling the gasifier temperature and not to worry about retaining high temperature to melt the ash components in coal. Using air will significantly simplify the gasification system and reduce the capital cost, but keeping the gasifier temperature above the ash fusion temperature is challenging. Especially small scale gasifiers could not maintain the gasifier temperature due to its inherent higher heat loss through the gasifier wall compared to large scale gasifiers.

If we consider the future gasifier plant that is to connect to CO_2 capture equipment, oxygen is the general trend. When air is used as an oxidizing agent, nitrogen is diluting the flue gas stream and will cost more in the downstream of CO_2 capture and separation.

Oxidizing agent	Oxygen	Air
Capital cost	High (ASU: about 15% of IGCC plant cost)	Moderate
Typical O_2%	95	21-24
CO_2 capture aspect	Competitive	Unfavorable
Heating Value of syngas	-	1/3 of O_2 case
Commercial gasifiers	All other coal gasifiers	Mitsubishi Heavy Industries, Japan

Table 7. Comparison of using oxygen and air for coal gasification

2.9. Power generation vs. chemical feedstock generation

The choice of coal gasifier could be different whether the final product is for electricity generation or for chemical product. Chemical product inherently requires more hydrogen in the molecular structure to be a higher value fuel like CH_4. Stable chemicals need to stabilize the structure as the $–CH_2–$ form which requires also more hydrogen.

Purpose	Power generation	Chemical feedstock
Target	Maximize total CO/H_2 amount Minimize heat loss Maximize efficiency	Maximize total H_2/CO ratio (Maximize H_2 content) Allow some heat loss Maximize high profit end-product
Gasifier material	High grade (expensive)	Not necessarily high grade
Gasifier size	Big (2,000-3,000 ton/day)	Moderate-Big (few hundreds - 3,000 ton/day)
Spare gasifier	Generally not in use	Usually use
Syngas cooling	Radiant syngas cooler	Quick quenching - moderate heat recovery
Typical gasifier type	Entrained-bed	Entrained, Fluidized, Fixed
Pressure range	22-28 bar (1st generation IGCC) 42 bar (1.5th generation IGCC)	Depend on the syngas conversion process pressure

Table 8. Choice of gasifier by the final product

Key question is whether one single gasifier can be utilized both as a power generating and also as a chemical feedstock producing gasifier. The answer is simply NO. Because plants that employ coal gasifier need 30-100 million US$ for the construction in general, the gasification plant should be designed and operated to optimize for the specific products unless the plant is designed as such from the very beginning.

2.10. Manufacturing limits

Manufacturing limit in the coal gasifier should be evaluated in terms of pressure, gasifier diameter, and manufacturing equipments. Coal gasifier is basically a pressure vessel which has a practical manufacturing limit simply by available steel rolling machine and by economics of manufacturing cost. Manufacturing a pressure vessel above 100 bar would not be practical purely due to the manufacturing ability of 3,000 ton/day scale gasifier as a single vessel, and it is never be economical since the wall thickness of large coal gasifier might be too large.

Pilot scale coal gasifiers are treating the coal in 1-30 ton/day range, in that no practical problem exists in manufacturing unless the size is too compact so that space for nozzles and cooling pipes is simply not available.

3. Coal selection guidelines for gasification [4]

The main content of this section had been published in the earlier paper in 2007[4]. Key parts are illustrated here. Table 9 illustrates what would be the most suitable coal for pilot-scale and commercial gasifiers. Pilot gasifier has a much smaller diameter in slag tap and gasifier exit line than the commercial size gasifier. If the ash content in feed coal exceeds 10%, simply small slag tap cannot pass through the molten slag even the slag viscosity is as low as liquid. Because slag flow viscosity in many cases stays at the few hundreds of centipoise range even above 1,400°C, smooth discharge of slag cannot happen, which results in plugging the slag discharge port.

Item	Pilot-scale gasifier	Commercial size gasifier
Coal rank	subbituminous	subbituminous, bituminous
Ash content	less than 5%, max. ~10%	8-12%, max. 25%
Volatile content	>30% (preferable)	No limit
Coal reactivity	high (preferable)	moderate-high
Ash viscosity	less than 250 poise at operating temperature	less than 250 poise at operating temperature

Table 9. Suitable coal for pilot and commercial scale gasifiers

The important indices for selecting the coal are ash melting temperature, slag viscosity, ash content, and the fuel ratio (or gasification reactivity). The suitable coal should contain the following properties. First, the approximate criteria for the ash melting temperature would be at the range of 1300-1400°C. If the ash melting temperature is below 1,260°C in particular, more precaution should be exercised to prevent the increased possibility of plugging by fly-slag. When the ash melting temperature is above 1,500°C, adding the fluxing agent would be required, or the gasifier temperature should be increased with the anticipated problems in the refractory life. Second, low-enough slag viscosity at the gasifier operating temperature must be guaranteed where slag would flow freely along the gasifier inner wall. Third, ash and sulfur contents should be at the lowest level if possible, and a certain amount of ash needs to be present in coal to protect the gasifier wall by thin-layer coating.

Coal reactivity is definitely an important parameter in coal selection for the gasification, probably next to the proper ash melting behavior. For the fixed gasifier volume, more reactive coal would complete the reaction within the available residence time. Before performing the actual gasification tests, coal reactivity should be studied by several ways. The most simple and intuitive way is to compare the fuel ratio of the proximate analysis data. Fuel ratio is defined as the weight ratio of fixed carbon to volatile matter contents in coal. A lower fuel ratio means more reactivity in general, such that lower rank coals are more reactive. The most simple and intuitive selection guideline that has been reported seems to be the plot between the fuel ratio that represents the coal reactivity versus the ash fusion temperature representing the slag viscosity. It can give the idea regarding the possibility in gasifier plugging [12,13].

Coals with the low fuel ratio would be a better choice if the gasifier would run without the char-recycling process. That means higher volatile content coals that normally exhibit a higher reactivity. To verify the suitable coal reactivity, TGA analysis under the inert gas environment would be sufficient to differentiate the relative reactivity of candidate coals in selecting the suitable coal. Figures 5-6 illustrate examples of applying TGA data to estimate the indirect reactivity by comparing with some reference coal that showed a good performance in gasification.

It has been reported that coal reactivity measured by TGA under an inert gas correlates with the inverse of the fuel ratio [7]. Although most accurate analysis data would be obtained under the identical gasification conditions, reactivity itself could be obtained from an analysis under inert environment. Here, reactivity was simply defined as the ratio of weight change over the specified reaction time.

In the dry-feeding gasifier, the surface moisture content of dried coal is more important than the total moisture data because of the pneumatic feeding requirement of the coal powder into the gasifier. Since the moisture content does not present any technical problems after coal is dried to less than 3 wt%, moisture content would not be a discerning factor in feeding ability. But the drying cost could reach too high to impact the total plant operating cost.

Slags obtained from the gasification at slagging temperature conditions leach heavy metal compounds far less than the environmental regulations, with no noticeable differences among the slag samples from different coal samples, and thus leaching test for slag would not be a precise criterion in determining the coal suitability for gasification.

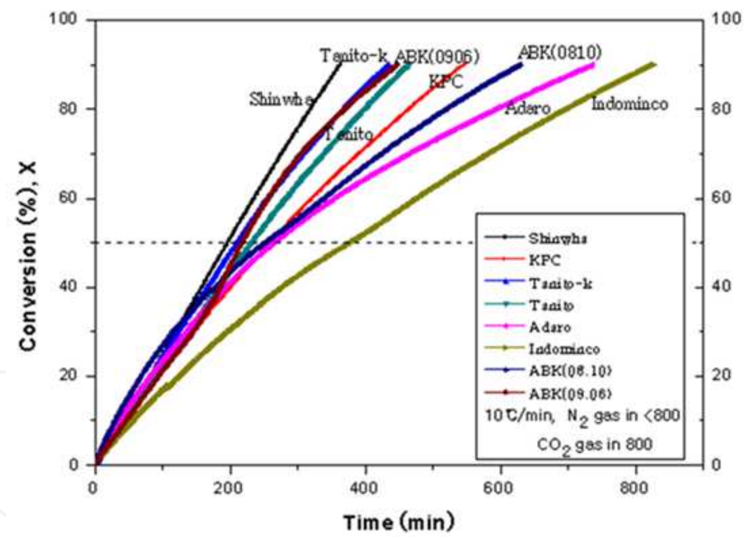

Figure 5. Rough comparison of reactivity for tested coals (TGA at Heating rate 10K/min till 800°C, 800°C isothermal, N_2 gas flow)

From the reactivity (indirect) point of view in Figure 6, Curragh and Denisovsky coals need a different gasifier design to account for longer reaction time.

Moisture content affects the operability of dry-feeding gasification system as well as the gasification efficiencies. Although moisture content of less than 2 wt% was used as a guideline in a dry-feeding commercial-scale coal gasifier [6], the moisture content of below 3 wt% demonstrated acceptable pneumatically conveying characteristics. In selecting the suitable coal for dry-feeding type gasifier, moisture content does not present any technical problems. It should rather be decided by economic consideration for drying and coal price.

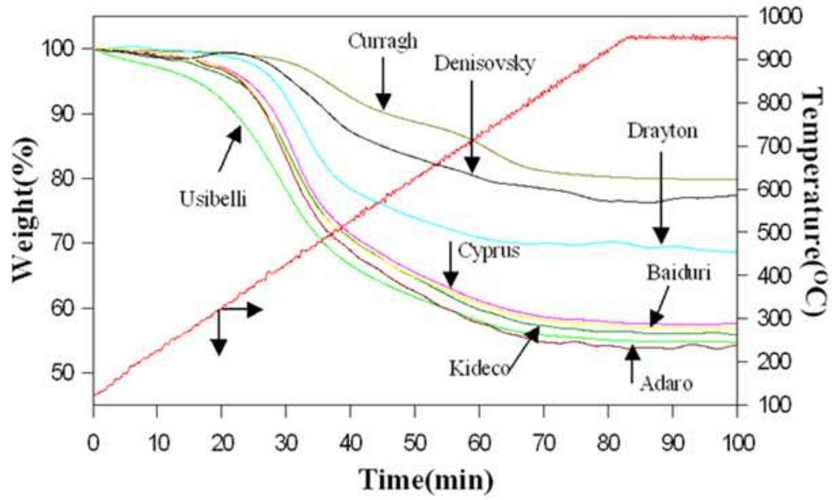

Figure 6. Indirect estimation of coal reactivity by TGA at 25 psig [4]

In gasifiers that require long-term continuous operation, low ash containing coals might be a better candidate since they produce a minimal fly-slag and bottom-slag that can act as a possible plugging material in exit-gas pipes or in the slag-tap. Judging from the operation results, the low ash containing coals showed significantly lower plugging problems by fly-slag in heat exchanging equipment like gas cooler after the gasifier.

On the other hand, because a certain level of ash in coal demonstrates a protecting function of the refractory as well as a function of heat loss minimization by coating the inner gasifier wall [8,9], an optimal ash content of the candidate coal should be judged on the basis of several interrelated parameters of coal price and ash-melting temperature. Since one of the many reasons for shutdowns in the demonstration IGCC plants of U.S.A., Europe, and Japan was slag and ash accumulation that can eventually develop to plugging and accompanying erosion, minimizing the fly-slag amount transported to the gasifier outlet is an area that should be scrutinized from the viewpoint of selecting the suitable coal. Coals of high ash content would definitely enhance the possibility of slag and ash accumulation.

Thereby, a preferable IGCC coal would possess only a reasonable amount of ash enough to coat the gasifier inner wall. The suitable ash content appears to be 1-6 wt% when there is a choice to select coal for the gasification system. For reference, a similar type of large-scale dry-feeding gasification indicated that coals containing less than 8 wt% ash content were recommended to recycle fly ash to coat the gasifier inner wall for insulating purpose, and the operating costs would increase from some 15% ash in coal[9]. Another reference reported that at least 0.5% ash is required to protect the gasifier inner wall when the wall is made of cooling tubes [10]. In addition, if coal is being imported or moved a long distance from the mine, higher ash content would only increase the cost for transportation and enhance the possibility of operational problems in gasifiers.

When the candidate coal meets the condition of ash melting temperature, another condition such as slag viscosity has to be considered. Suggested minimum gasifier operating temperature applicable in the dry-feeding gasifier was reported to be 50°C above the crystalline temperature of molten slag or 50°C above the temperature that corresponds to the 1,000 poise of slag viscosity for glassy slags [11]. Crystalline temperature is defined as the point where slag viscosity commences to increase sharply with decreasing temperature. Typically for the best performance, the gasifier is operated while maintaining the slag viscosity at the below 250 poise level. However, for practical applications, it would be better to maintain the gasifier temperature at about 100°C above the measured ash fluid temperature. All in all, slag viscosities of coals showing the glassy slag behavior were higher than those of molten slags above the crystalline temperature, signifying that more operational plugging problems by slag might occur for the coals of glassy slag.

Gasification temperature has a range for the proper conversion efficiencies. Typically, it is between 1,300-1,600°C. Oil gasification temperature is in the range of 1,300°C while the solid gasification operates at the higher temperature range. If the operating temperature is too low, carbon conversion gets lower mainly by insufficient reaction.

Coal selection can be summarized as follows. Coal properties of ash melting temperature, slag viscosity, ash content, and fuel ratio can be used as guides for estimating the plugging probability and gasification reactivity. First of all, the ash melting temperature and corresponding slag viscosity were used as a guide data for suitable coals. Next, low-rank coals of high reactivity were selected as the best candidate coals for dry-feeding entrained-bed coal gasification operation. Then, low ash coal would be chosen for the possibility of reduced operational problems related to slag and ash. Although the drying process would increase the cost for the subbituminous coals, more reactive coals with appropriate ash melting temperature should be the choice for dry-feeding entrained-bed gasification.

4. Application of CFD for gasifier design [5]

Although there have been several successful coal gasifiers that were commercially proven, many different design configurations are still possible for simple and reliable gasifier operation. As can be expected, tests of coal gasifiers at the actual high pressure and temperature conditions cost a lot of time and fund. Powerful simulation tools have made a major progress in computer simulation for the detailed analysis in reactors. It became a normal procedure to check the details in reactor design by CFD (Computational Fluid Dynamics). There are many limitations in applying CFD method in gasifier design, particularly in estimating slag behavior and slag-tap design. However, the CFD analysis proved to be useful in comparing the widely different design concepts as a pre-selection tool.

First, cold-flow simulation is applied to pre-select the configuration concepts, and the hot-flow simulation including chemical reactions follows to compare the concepts at more similar actual gasifier operation situation.

In designing a gasifier, many design parameters should be compared to obtain the optimal performance. Among design parameters for the entrained-bed gasifier, syngas flow direction, expected temperatures exiting the gasifier, size of any dead volume, L/D ratio, residence time inside the gasifier, and number and location of burner nozzles are most important.

From the relative evaluation of this preliminary analysis, most promising type and shape of the gasifier can be selected, after which more detailed CFD analysis including chemical reactions follows in order to obtain profiles of temperature, gas compositions, and particle flow path, etc.

As an example of CFD illustration, four cases of gasifier configuration of dry-feeding were first selected with two up-flow designs and two down-flow designs, as illustrated in Figure 7. In all cases, the feeding nozzles were positions to form a cyclonic swirl inside the gasifier with the purpose of increasing residence time. Case 1 is a reference design that is similar to the 3 ton/day coal gasification pilot plant at IAE in Korea. Thus, actual coal gasification database with more than ten different coals is available to verify the results in Case 1.

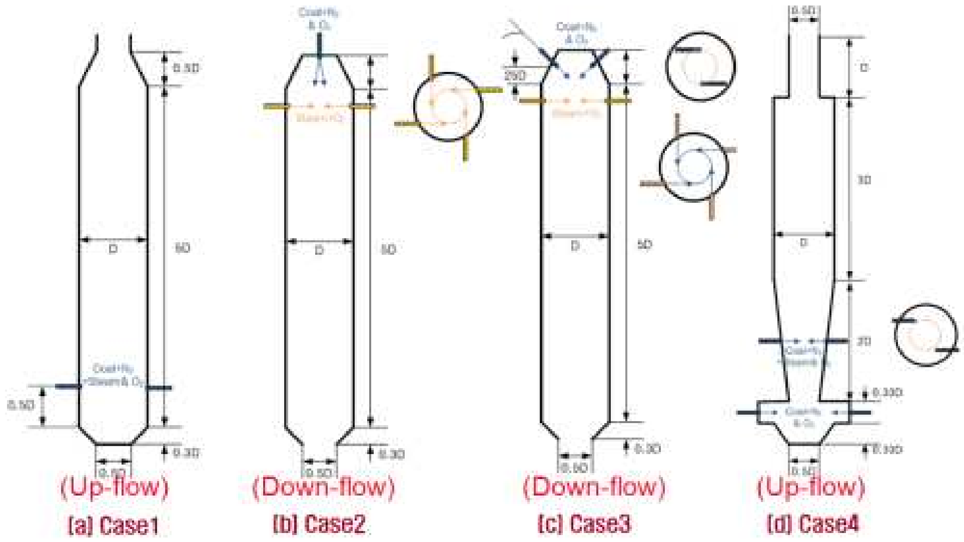

Figure 7. Four coal gasifier configurations compared in the CFD analysis [5]

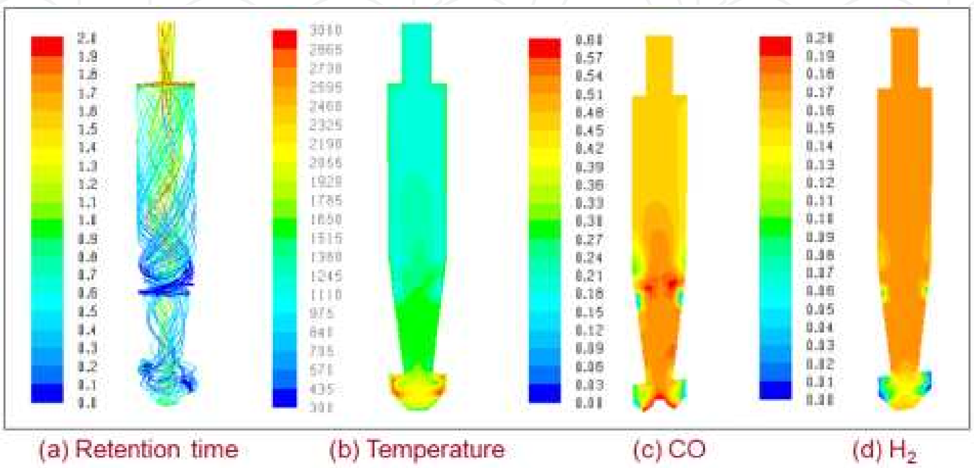

Figure 8. Hot-flow simulation result for up-flow Case 4 [5]

Table 10 summarized the hot-flow analysis results. Gas-phase residence time in Case 4 shows the highest value as 1.43 sec, while the down-flow Case 2 exhibited lowest as 1.03 sec. Residence time in reference Case 1 was 1.17 sec.

The pilot-plant gasification data in Case 1 configuration showed above 98% carbon conversion for the highly reactive Indonesian subbituminous coals [3]. For some un-reactive bituminous coals at the pilot gasifier of Case 1 configuration, residence time was not sufficient to guarantee the full carbon conversion in one pass through the gasifier. Recycling of un-reacted char particles to the gasifier, which means several passes through the gasifier, is one option to cope with this kind of low conversion efficiency in one pass, although more capital investment is required for additional equipments. In short, CFD analysis will be supplemented with actual pilot test results for the final design of the coal gasifier.

Case		1	2	3	4
Gas residence time (sec)		1.17	1.03	1.26	1.43
Gasifier exit gas temperature (°C)		1,202	1,081	1,065	1,021
Gasifier exit gas Comp. (vol %)	CO	54.13	52.81	52.70	51.46
Gasifier exit gas Comp. (vol %)	H_2	16.37	17.09	17.25	18.12

Table 10. Hot-flow gasifier CFD simulation result [5]

5. In-situ estimation of gasification status inside gasifier

Operating pilot coal gasifier produces profiles as in Figure 9. Gasifier temperature, pressure, and syngas composition are most basic data that are measured. In the pilot gasifier, inside temperature is measured directly by thermocouples in order to know the actual gasification condition. Syngas composition is readily measured by on-line GC or dedicated on-line gas analyzers.

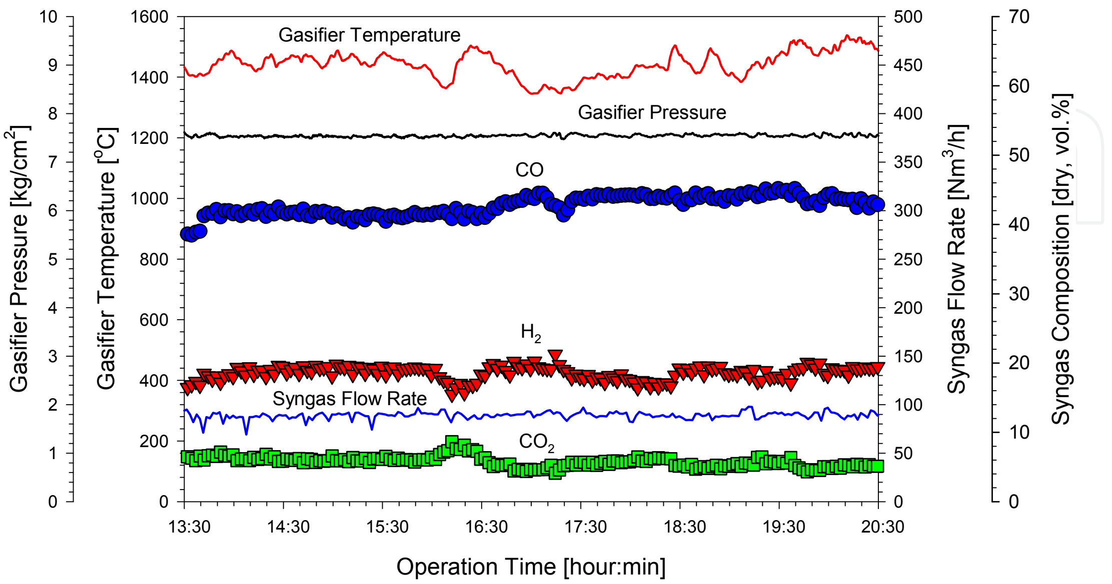

Figure 9. Typical gasification profiles at pilot scale dry-feeding coal gasifier (8 bar, Indonesian KPC coal)

If the gasification temperature is higher than 1,400ºC where the chemical reaction is so fast that mass transfer limitation prevails, syngas composition can be reliably approximated by the thermodynamic equilibrium calculation which is readily available in most commercial process simulation softwares like ASPEN.

Examples of estimating the syngas composition by thermodynamic equilibrium calculation are shown in Figures 10-11. Both figures illustrate estimated syngas composition is satisfactory in engineering sense. In pilot plant, a notebook computer is used to calculate the expected syngas composition at the certain carbon conversion and reaction temperature while the gasifier is operated. In opposite way, from the known information on syngas composition, temperature, and coal property during the gasifier test, carbon conversion at that time can be calculated to verify how the gasifier is being operated.

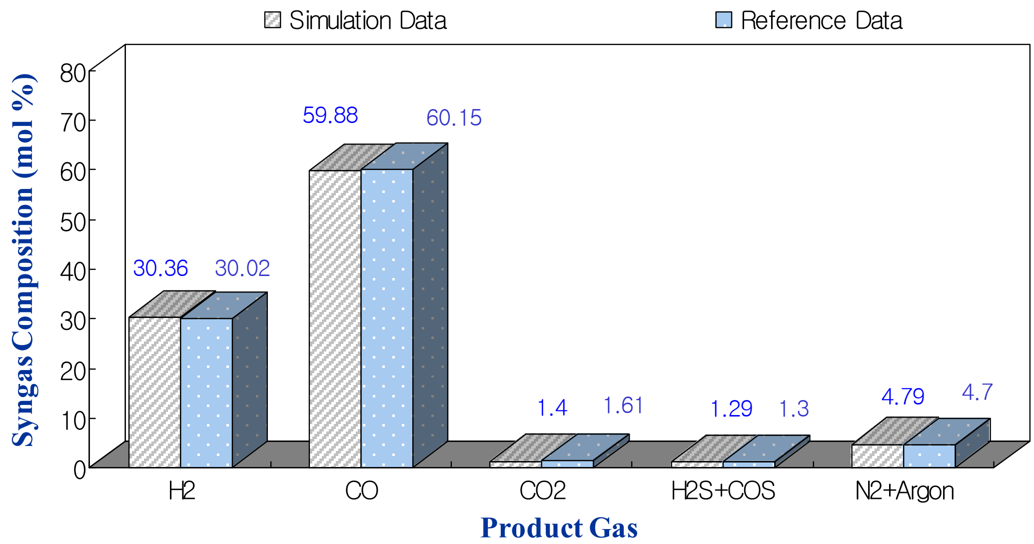

Figure 10. Comparison of syngas composition between simulated and actual commercial-scale plant data for Illinois No. 6 coal

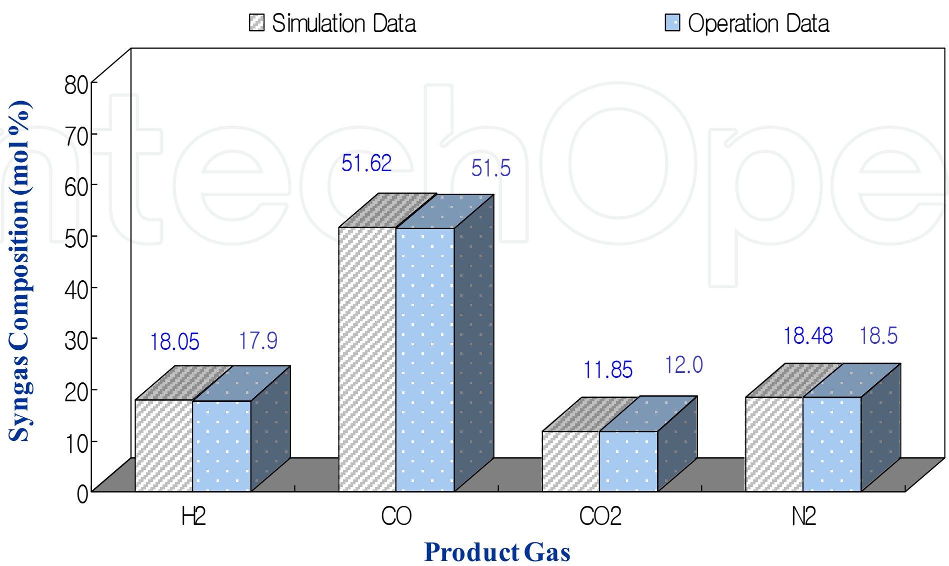

Figure 11. Comparison of syngas composition between simulated and actual pilot plant data for Indonesian subbituminous coal

Because the coal gasifier is normally under the pressure, direct looking into the gasifier is impossible. While we operate the gasifier, there are important variables to know in-situ, if possible, such as reaction temperature (typically 1,400-1,600°C), pressure, gas composition, and slag flow.

Gasifier temperature measurement by R-type thermocouple is a normal method in pilot plants, but in commercial gasifiers where at least several months of continuous operation is required thermocouple proved to be unreliable due to frequent wire disconnection under hot corrosive environment. Most commercial plants acquire temperature information indirectly by measuring such as steam production amount from the gasifier wall or methane content. Methane content in syngas has exhibited a reliable indirect information on temperature high or low limit, which is a very important data to prevent significant gasifier damage. If the gasifier temperature is too high, gasifier wall might be damaged, and if the temperature is too low, then the slag tap would face a plugging by re-solidified slags.

Figure 12 show the increase of CH_4 % from about 0 to 6,000 ppm by the drop of 100°C in gasifier temperature from 1,450°C to 1,350°C. Typical slagging coal gasifiers operate at temperatures where CH_4 content is maintained below the certain guideline value.

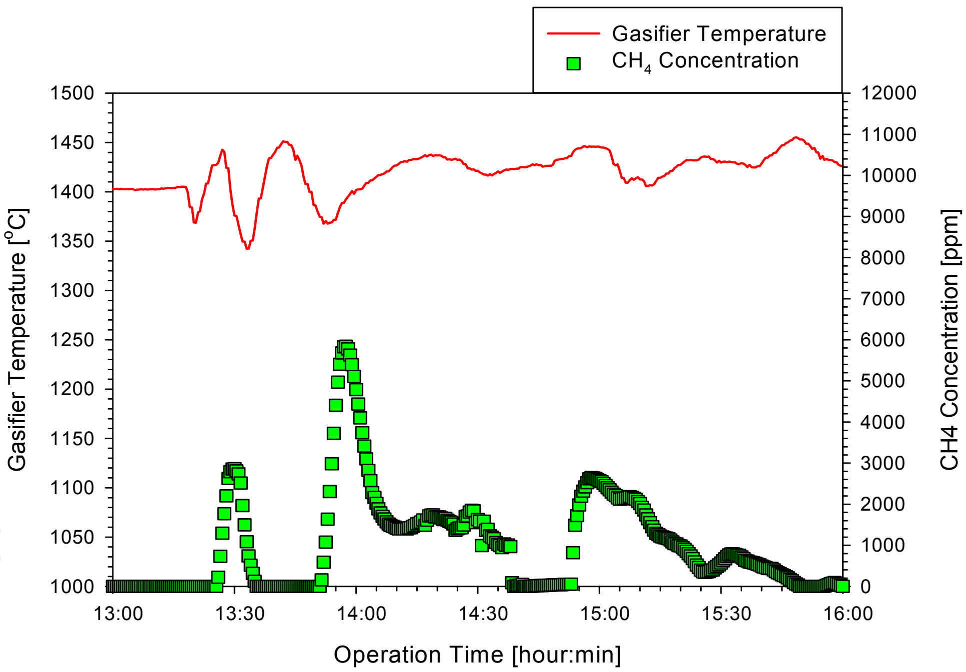

Figure 12. Relationship between gasifier temperature and CH_4 content (10 bar, Indonesian KPC coal)

6. Key areas of operation problems

There are key problematic areas that should pay attention in design and during operation. Main gasifier body would not explode unless a really bad manufacturer was chosen. There are weak points in gasifiers, which are slag tap, syngas exit line, and feed nozzles. Pilot plant requires frequent disassembling and reassembling to see the inside part and take samples for analysis after the test, which would increase the risk by many joint areas.

Gasifier problems basically reside in uncontrolled fluctuation of coal/oxygen, slag behavior, syngas leakage, and nozzle area. Smooth feeding is an essential part in all chemical reactions. In coal gasification, it is more important. A small sudden increase of oxygen while the coal feed is same can increase the gasifier temperature above 1,600°C in 10-30 seconds. Slag and molten fly-slag plug the slag tap and exit pipes or syngas cooling zone, if not properly monitored and operated. Many joint areas that are frequently reassembled inherently possess the possibility of loosening and eventually leakage with time. In the pressurized coal gasifier containing hot syngas whose components CO and H_2 are all easy to ignite with atmospheric oxygen, loosening joints definitely lead to syngas leakage, and surely a noisy explosion of that area.

6.1. Slag tap

The biggest operational problem identified during the pilot-scale gasification tests were the plugging in the slag discharge port by the bottom slag and the plugging in the syngas outlet area of the gasifier by the fly-slag, with the possibility of backfire explosion in the area of feed-lance nozzles. From the aspect of plugging by slag, slag viscosity with the gasifier temperature is an important index as described in the previous section for selecting the suitable coal. From the viscosity point of view, all subbituminous and most bituminous coals have shown the low enough slag viscosity among the tested coals, and thus it seems that they would not cause any operational problems by slag flow at the proper operation temperature, whereas a Russian coal yielded the highest slag viscosity that had caused an operational problem in slag discharge even under the gasifier temperature above 1,500°C. Higher ash content in coal increased the possibility of slag-related operational problems.

6.2. Syngas exit line

The most troublesome coal with plugging by fly-slag at the syngas outlet was Alaskan Usibelli coal from USA that showed an ash fluid temperature of 1,257°C. Figure 13 shows Alsakan Usibelli coal case of exit line plugging by fly-slag. Contrary to the case of Russian coal where slag viscosity values were more representing the actual behavior of slag in the gasifier, Usibelli coal demonstrated that ash fluid temperature for the raw coal was more representing the actual behavior of slag viscosity in the gasifier than the viscosity measurement for the gasified slag. Viscosity in the fly-slag of Usibelli coal exhibited at least

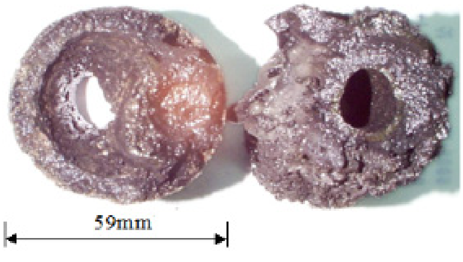

Figure 13. Deposited ash/slag at the exit port of pilot-scale coal gasifier (Alaskan Usibelli coal, 8 bar, 1,450°C)

a similar melting behavior that could be represented by the ash fluid temperature. The result till now signifies the importance of actual testing under the gasification conditions to confirm the gasification characteristics including the slag behavior.

Caution should be exercised when the candidate coal shows very low ash fusion temperature below 1,260^{o}C with high ash content because the heat recovery system attached to the gasifier might show a higher plugging tendency.

6.3. Feed nozzle area

In the feed nozzle area, coal powder or coal slurry, oxygen, steam, hot syngas all meet at the small space. Moreover many joints exist, and mechanically nozzle itself contains many layers of metal tubes that expose to hot corrosive syngas. Welding points must meet the stringent specification to guarantee the long operation, and thus most gasifier vendors still supply the feed nozzles under their quality control.

If the welding joint in the feed nozzle break, syngas can pass though the hole and make the metal weak to break in sequence, which eventually ends up in explosion of feed nozzle area. More detailed discussion follows in the next section.

7. Safety consideration in coal gasification pilot plants

Institute for Advance Engineering in Korea has operated the pilot coal gasifiers from 1994, and has experienced several safety issues. During the design of the coal gasifier and the preparation of the constructed gasifier operation, items that need most careful concentration are,

- Maintain the enough higher pressure difference all the time at the coal feeding equipment over the gasifier
- Make sure that connected lines would not leak
- Welded area that would be exposed to hot syngas should be minimized
- Weakest and most dangerous area is the coal/oxygen feeding nozzle lines
- Toxicity of CO
- Any slightest possibility of contacting CO and Ni-based catalysts to produce nickel tetracarbonyl ($Ni(CO)_4$) which is one of the most fatal compound, more hazardous than CO

Coal gasifier deals with the syngas that consists of mainly CO and hydrogen at the high pressure and high temperature. Gasification also involves the pure oxygen with the coal powder or coal slurry. Under the normal operating situation in that reactive coal and oxygen are moving to the lower pressure region, coal and oxygen are reacting on the way through the gasifier and syngas are formed. Pressure at the coal feeding vessel remains at the higher pressure than the gasifier, so that hot syngas is not damaging the feeding lines. At any time, this pressure difference must be guaranteed, otherwise hot (1,300-1,600^{o}C) syngas will flow backward through the coal powder and oxygen lines that will surely make an explosion.

Figure 14 shows the syngas flame along with the ignited coal particles that are flying around the flame at the leaked feed nozzle area. The accident occurred by the loosened ferrule at the coal feeding nozzle of the dry-feeding pilot coal gasifier that operated at 8 bar and around 1,450°C conditions. This flame looks similar to the flame of welding torch.

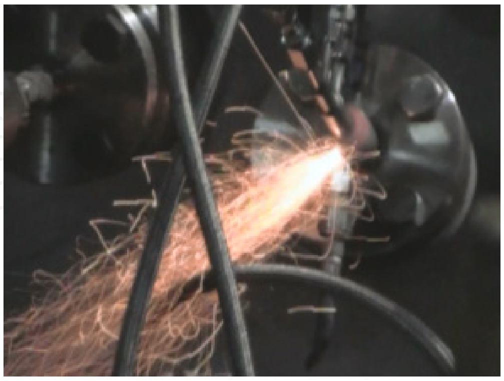

Figure 14. Picture showing the syngas flame caused by syngas leakage at the feed nozzle area

Figure 15. Damaged valve main body by the syngas explosion occurred during the 10 bar and around 1,500°C gasification pilot plant test

The force by the syngas explosion that occurs typically by the backward pressure to the feeding line amounts to tear out instantaneously the SUS metal of the value that should withstand 1,500 psi. Figure 15 demonstrates the damage to the valve main body by the syngas explosion occurred at the 10 bar and around 1,500°C conditions. The explosion should be avoided, but if it happens the damage area should be minimized. Best routine is to prevent any personnel who goes near the nozzle area during the hot gasification test. The explosion happens with a very short loud blast and will hiss out the syngas until the majority of syngas is vented out. Normal emergency routine involves the pushing the syngas out of the gasifier with nitrogen which is all the time maintained at the higher pressure than the gasifier and the oxygen line.

Figure 16 also exhibits the force of the syngas explosion. In the Figure, right-hand side is the gasifier (not shown in the figure) and the coal feeding vessel (not shown in the figure) is located at the left side of the Figure. There was a leak in the connecting tubes on the left side of the Figure. Then pressure of the feeding line suddenly drops to atmoshperic pressure and the hot syngas gushed to the feeding lines. Hot syngas reacts with coal powder and pure oxygen existing in the feeding line, resulting in the very explosive gas and push directly from the gasifier through the feeding line. Damaged shape in the Figure clearly illustrates the direction of the syngas explosion which is not following the curved SUS pipe, rather moves in direct line and tear the pipe in that direction.

Figure 16. Damaged SUS coal powder feeding pipe occurred during the 8 bar and around 1,500°C gasification pilot plant test

Figure 17 shows the importance of the welding quality in the feeding nozzle area. The accident occurred during the pilot coal gasifier operation with a subbituminous coal at 20 bar, 1,400°C. After the accident the nozzle parts were scrutinized and revealed that the vertical welding on the water cooling zone was an initial starting point and the hot syngas moved through the cooling water zone, after which the nozzle itself was damaged and finally the syngas with pure oxygen resulted in explosion. In the commercial system, water cooling system is operated with higher pressure than the gasifier pressure, but in the pilot system that might not use the high pressure water facility, the nozzle area should be monitored carefully and should make a way to prevent the possibility of syngas leakage through the cooling zone.

Carbon monoxide in syngas is typically 20-60% in the pilot coal gasifiers. Considering the allowable limit of CO concentration is 50 ppm and exposure to 0.1% CO can lead to fatality, the concentration of 20-60% which amounts to 20,000-60,000 ppm can lead to extreme safety hazards. Just one inhaling of syngas is enough to make a person to serious dizziness and vomiting.

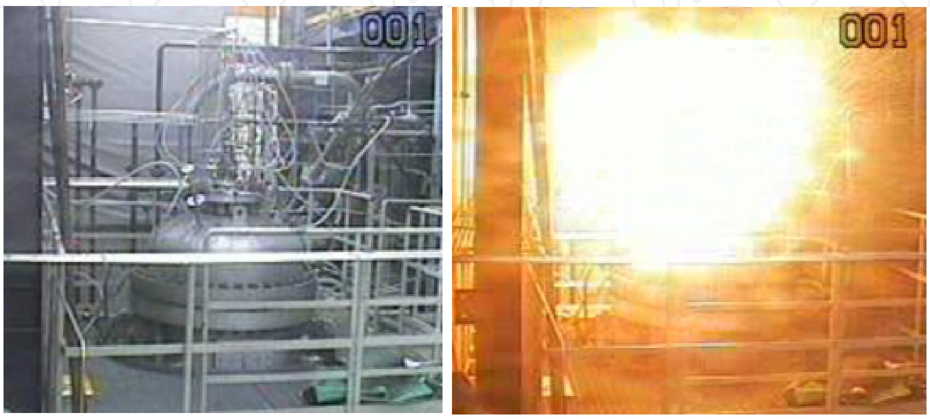

Figure 17. Explosion accident at the coal feeding nozzle during the pilot gasifier operation at 20 bar, 1,400°C (Left: picture at normal operation, Right: picture at explosion time)

Syngas is widely in demand for manufacturing chemicals or synthetic fuels, which normally involves catalytic reactions. Extreme caution should be exercised when any nickel containing catalysts are employed with syngas. Although the chance is slim and little amount is used just as a test, any possibility inducing the formation of Nickel tetracarbonyl ($Ni(CO)_4$) should be checked and even the slightest inhaling by personnel should be avoided. Nickel tetracarbonyl is one of the most fatal compound, more hazardous than CO.

8. Future direction of coal gasifiers

If the commercially available coal gasifiers have reached already the best efficiency and satisfied all the industrial requirements, there would be no need to design and construct the pilot-scale gasifiers. Current coal gasifiers are still too expensive and too small in terms of coal-fired power plant. Coal price generally linkages with the oil price. Since the high oil price prompts to use more coal and pushes the coal price accordingly, low grade coal would be utilized more widely in the near future. Also there is a CO_2 issue that will impact the gasifier technology more suited in the CO_2 capture.

The future direction of R&D for coal gasifiers can be summarized as follows:

- Bigger capacity in a single gasifier
- Simplification of gasifier design
- Compactness
- Use of cheap low-grade coal
- Reduction of construction cost
- Increase in plant availability
- Response to CO_2 issue

9. Conclusions

Purpose of testing with the pilot-scale coal gasifier is to confirm the design concept before going to the commercial scale. In a sense, pilot gasifier is more dangerous than the big scale gasifier because the pilot gasifier requires frequent disassembling and contains more joint parts with smaller slag passage hole, which will increase the possibility in syngas backflow with eventual explosion. With knowing what is going on in the gasifier with the specific choice of design options, the best selection and design for the gasifier would possible.

Even with the long history of developing and commercial use of coal gasifiers, there is still a room in upgrading to a more efficient and cheaper version of coal gasifier and the pilot scale gasifier should follow to confirm the design logic and practical applicability. On the way to make a next generation coal gasifier, fundamental issues and experience from the past should be used as a cornerstone. Although it is not a vast experience compared to the almost century-old gasification system as in the fixed-bed type, the pilot-scale experience at IAE for the entrained-bed type gasifiers during the last 18 years or so might be useful for providing as guidelines which can act at least as a blocking block in preventing the worst case and act as a new starting point.

Author details

Yongseung Yun*, Seung Jong Lee and Seok Woo Chung
Institute for Advanced Engineering, Suwon, Republic of Korea

Acknowledgement

This work was supported by the Development of 300 MW class Korean IGCC demonstration plant technology of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government Ministry of Knowledge Economy (*No. 2011951010001B*).

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