# DEVELOPMENT AND OPERATION OF LARGE SCALE CIRCULATING FLUIDIZED BED COAL GASIFICATION

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**Abstract** – Coal will continue to be the predominant energy resources of China. Gasification is one of the key technologies for the high efficiency and clean use of coal resources. Institute of Engineering Thermophysics (IET) has developed CFB gasification technology and achieved industrial application. This paper aims to summarize our work in area of CFB coal gasification. Till now, 28 sets of industrial CFB gasification systems were completed, with fuel gas production capacity ranging from 15000-60000 $Nm^3/h$. Some novel key technologies are developed and conducted in the industrial CFB gasifier, such as counter-current air cap technology, air preheating technology, direct slag disposal technology, multi-stage self-balanced char transporting technology and so on. Industrial investigations were conducted in different scale of gasifier. The effects of coal types, fuel gas production capacity and the output percentage of the full load were studied. The produced fuel gas can meet the production requirements of the subsequent process. The cold gas efficiency ranges from 63.33% to 77.31%, the carbon conversion ranges from 80.33% to 87.42%, and the net calorific value of fuel gas ranges from 5.23 to 6.01 $MJ/Nm^3$. In addition, the fuel gas production can be easily tubed from 50% to 110% of the full load. The results indicate that CFB gasification is an efficient and clean coal conversion technology, with wide fuel flexibility, simple flow process and high social recognition.

## INTRODUCTION

China is rich in coal, but short of oil and nature gas. Coal will continue to be the predominant energy resources in many countries worldwide, especially in China. Direct combustion of coal is associated with several problems regarding both the environment and the production requirements. Coal gasification technology is very popular in China, which can meet the environmental requirements and satisfy the steadily increasing demand in clean fuel gas production and chemical raw gas production as well.

Circulating fluidized bed (CFB) gasification of carbonaceous solid fuels is a well-established technology. In CFB, solid particles are held by fluidization agent to form a liquid-like gas-solid mixture. The intensified gas-solid mixing not only enhances mass transfer, but also the heat transfer to internal surfaces and between solid particles and gas. CFB usually operates at moderate temperatures (850-1000 ºC) and can achieve desulphurization within furnace. Moreover, a broad variety of fuels could be used in CFB, and this is actually another important advantage of the technology. In case of the used fuels, coal has been widely used so far and will play an important role for the foreseeable future, especially in China.

However, great challenges are associated with CFB gasification. Because gas and solids in CFB are a heterogeneous mixture with liquid-like behavior. The reactions taking place in CFB is complicated. Therefore, the scale up of CFB gasifier to commercial size is a changeling task.

Institute of Engineering Thermophysics (IET) has developed CFB gasification technology with independent intellectual property rights. This technology uses coal or other carbonaceous solid fuels as feedstock for production of industrial fuel gas. Till now, 7 series of production system are formed, including fuel gas production capacity of 15000, 20000, 25000, 30000, 35000, 40000 and 60000 $Nm^3/h$, and 28 sets industrial CFB gasifiers have been designed and built up. The produced fuel gas could be used to provide heat for wide range of fields, such as $Al_2O_3$ calcination, magnesium refining, nickel-iron alloy refining, glass production, coking and so on. Table 1 shows some typical commercial applications of CFB gasification. The process characteristics, the used key technologies and the operating performance could be discussed briefly.

This paper provides an overview of our work in area of CFB coal gasification. Investigations were performed with different scale of industrial CFB gasifiers. Significant efforts have been made to improve gasifier design and enhance gasification performances. The effects of coal types, fuel gas production capacity and the output percentage of the full load were investigated.

Table 1 Typical commercial applications of CFB gasification with different fuel gas production capacity

| Fuel gas production capacity ($Nm^3/h$) | User | Product property | Completed time | Sets |
|---|---|---|---|---|
| 25000 | Jiangsu Huiran | hot fuel gas | 2013.08 | 2 |
| 40000 | Shandong Xinfahuayu-stage I | cold fuel gas | 2014.4 | 1 |
| 60000 | Hebei Jiujiang jiaohua | cold fuel gas | 2015.08 | 1 |

## PROCESS PRINCIPELE

The key components of the gasification system is the CFB gasifier, which is consisted of a riser, single/multiple cyclone, and single/multiple loop seal. Coal or other carbonaceous solid fuel is added to the riser from the middle or the bottom of the riser. Gasification agent is introduced to the system from the bottom of the riser. Silica sand is most commonly used as bed material. The fluidized bed material ensures good mixing of the fed fuel as well as the reaction heat.

The added fuel undergoes rapid drying, pyrolysis reaction to release volatile matter. The resulting chars undergo combustion and gasification reactions to generate fuel gas. The produced fuel gas, unreacted chars and bed material enter into the cyclone to achieve solid-gas preliminary separation. The separated chars and bed material are returned to the riser through loop seal, which is helpful to recover the heat and enhance the conversion of the residual carbon in recycling char. The bottom char is discharged from the bottom of the riser. The fuel gas carrying some ultra-fine ash particles leaves the gasifier, and the subsequent process can be tuned according to user's production requirement.

## TYPICAL FLOWSHEET AND NOVEL KEY TECHNOLOGIES

Fig.1 shows an example of industrial CFB gasification flowsheet for production of cold fuel gas. The whole system consists of a CFB gasifier, a coal feeding system, an air supply system and an auxiliary system. Coal is supplied via a screw feeder from the hopper into the riser. High temperature air (preheated by the air preheater) and steam (produced by the waste heat boiler) are mixed and then introduced through air cap to the riser. The flows are individually controlled by mass flow controllers. Temperature measuring ports and pressure drop measuring ports are placed along the height of the riser and fuel gas pipe, which are effective monitoring methods to guarantee the smooth operation of the CFB gasifier. The produced high temperature fuel gas undergoes air preheating system, heat recovery boiler and gas cooler to recovery heat, and then undergoes bag filter to remove dust. The cold and clean fuel gas is pressurized and sent to the subsequent process. The main gas components of $H_2$, CO, $CO_2$ and $CH_4$ are analyzed according to GB 12208-2008 (Test methods of components and impurities of the manufactured gas). For flowsheet of hot fuel gas production, the produced high temperature fuel gas could be directly sent to the subsequent process.

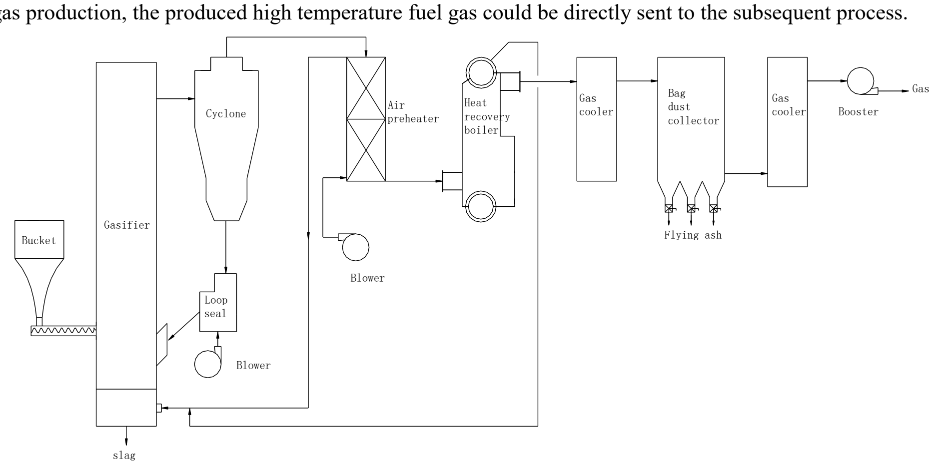


Fig.1 Industrial CFB gasification flowsheet for production of cold fuel gas

Some novel key technologies are developed and conducted in the industrial CFB gasifier:

(1) Counter-current air cap technology is used in the industrial CFB gasifier, which can not only meet the requirements of uniform air distribution, but also prevent the leakage of ash. In addition, the air distributing resistance can be tuned by regulating the speed of gasification agent through the distributor hole of cap.

(2) Air preheating technology and waste heat reboiler are used to recovery the fuel gas heat step by step. Through air preheating technology, the physical heat of high temperature flue gas is transferred to air. About 650 $^{o}$C of the preheated high temperature air is introduced to the riser. This technology is useful to reduce the combustion percentage of carbon, increase the net calorific values of fuel gas and cold gas efficiency.

(3) Multi-stage self-balanced char transporting technology is developed to meet the requirement of large fuel gas production capacity. Through this technology, the recycled solid particles can be transformed from the low pressure side to the high pressure side. Moreover, the multi-stage self-balanced char transporting technology can inhibit the leakage of fuel gas from riser to cyclone.

(4) Direct slag disposal technology is used to achieve a large cross-section uniform distribution of gasification agent. Using this technology can achieve the successful disposal of big char particles. High temperature and long-term stable operation could be realized. In addition, for shutdown process, the unexpected explosion can be inhibited effectively.

## FUEL CHARACTERISTICS

The proximate and ultimate analyses of coals are given in Table 2. Shenmu coal was obtained from Shan'an xi province, Shanxi coal was obtained from Shanxi province, Inner Mongolia coal was obtained from Inner Mongolia, Nuojin coal and Shuozhou coal were obtained from Shanxi province. The size of the used coal particles is within the range of 0-10 mm.

Table 2 Properties of the used coals

| Item | Shenmu | Shanxi | Inner Mongolia | Shuozhou | Nuojin |
|---|---|---|---|---|---|
| Proximate analysis (wt.%, ar) | | | | | |
| $M_{ar}$ | 12.0 | 10.8 | 16.4 | 17.4 | 14.8 |
| $A_{ar}$ | 7.26 | 17.68 | 9.38 | 18.79 | 5.42 |
| $V_{ar}$ | 31.38 | 25.25 | 26.13 | 25.14 | 26.76 |
| $FC_{ar}$ | 49.36 | 46.27 | 48.09 | 38.67 | 53.02 |
| Ultimate analysis (wt.%, ar) | | | | | |
| $C_{ar}$ | 65.25 | 57.89 | 60.06 | 47.8 | 64.48 |
| $H_{ar}$ | 3.97 | 3.48 | 3.18 | 2.88 | 3.46 |
| $N_{ar}$ | 0.87 | 0.94 | 0.95 | 0.74 | 0.79 |
| $O_{ar}$ | 10.3 | 8.44 | 9.61 | 11.93 | 10.81 |
| $S_{ar}$ | 0.36 | 0.77 | 0.43 | 0.47 | 0.24 |
| $Q_{net,ar}$ (MJ/kg) | 25.36 | 22.3 | 22.84 | 17.69 | 24.45 |
| Ash fusion temperatures (°C) | | | | | |
| DT | 1130 | 1460 | 1330 | >1500 | 1120 |
| ST | 1140 | >1500 | 1350 | - | 1120 |
| HT | 1140 | - | 1360 | - | 1130 |
| FT | 1150 | - | 1370 | - | 1180 |

ar, as received. $FC_{ar}$ and $O_{ar}$ are obtained by difference.

## INDUSTRIAL OPERATION

Industrial operations of CFB gasification were conducted in different scale of gasifiers. The fuel flexibility, fuel gas production capacity and the output percentage of the full load were studied. Table 3 shows the experimental operating conditions and the main results of all cases. Air and steam were used as gasification agents. The gasification temperature was tuned by regulating the ratio of coal to gasification agent, and controlled at about 930-950 ºC. Fig.3 compares the main gasification performances of all cases studied in this work.

Table 3 Experimental parameters and main results

| Cases | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Production capacity | 25000 $Nm^3/h$ hot flue gas | | 40000 $Nm^3/h$ cold flue gas | | 60000 $Nm^3/h$ cold flue gas | |
| User | Jiangsu Huiran | | Xinfa huayu-stage I | | Jiujiang jiaohua | |
| The used coal type | Shenmu | Shanxi | Inner Mongolia | | Shuozhou | Nuojin |
| Temperature of gasifier / ºC | 945 | 932 | 945 | 930 | 950 | 951 |
| Coal feeding rate / (kg/h) | 8300 | 5290 | 13950 | 10480 | 24638 | 21007 |
| Air / ($Nm^3/h$) | 16970 | 9930 | 23170 | 15000 | 35598 | 34544 |
| Clean fuel gas / ($Nm^3/h$) | 26250 | 14218 | 41005 | 28926 | 65833 | 63935 |
| Output percentage of full load / % | 105 | 57 | 103 | 72 | 110 | 107 |

A fuel gas production capacity of 25000 $Nm^3/h$ CFB gasification system was built in Jiangsu of China in Aug. 2013, and the outline of the industrial plant is shown in Fig. 2(a). The required product is hot fuel gas. The produced fuel gas was used to provide heat for rotary furnace. Some novel key technologies were used in this system, such as counter-current air cap, air preheating technology and direct slag disposal technology. The fuel gas production and fuel flexibility were investigated. For case A, Shenmu lignite was used as feedstock. At conditions as illustrated in Table 3, the fuel gas production is about 105% of the full load and the net calorific value of fuel gas is 5.23 $MJ/Nm^3$. For case B, Shanxi lignite was used as feedstock, the fuel gas production is about 57% of the full load, and the net calorific value of fuel gas is 5.25 $MJ/Nm^3$. The cold gas efficiency and the carbon conversion for the cases are very close, and no obvious difference was observed for the whole operating process, indicating satisfied regulating capacity of fuel gas production.

Shandong Xinfa Huayu is focused on the production of alumina. The original gas station had 89 sets of Φ3.2m two-stage fixed-bed gasifier. Every 6 sets of gasifier was a group with fuel gas production of 6×6000 $Nm^3/h$. Considering the environment threat and manufacturing cost, 5 sets of CFB coal gasification systems were built to replace the obstacle two-stage fixed-bed gasifier. Briefly, 1 set of 40000 $Nm^3/h$ CFB coal gasification system (stage I) was built in Apr. 2014, 2 sets of 40000 $Nm^3/h$ CFB coal gasification systems (stage II) were built in July, 2015, and 2 sets of 60000 $Nm^3/h$ CFB coal gasification system (stage III) were built in Dec. 2016. The produced fuel gas was used to provide heat for alumina calcination. The experiments were performed in the stage I of 40000 $Nm^3/h$ CFB coal gasification system. The flowsheet of the gasification system is shown in Fig.1, and the outline of the industrial plant is shown in Fig. 2(b). Multi-stage self-balanced char transporting technology was firstly used in the gasification system. Inner Mongolia lignite coal was used as feedstock, and the operating load of the gasifier was evaluated. As shown in Table 3, for case C and case D, the fuel gas productions are 41005 $Nm^3/h$ and 28926 $Nm^3/h$, respectively, which are correspondingly to 103% and 72% of the full load. For case C, the average volume concentrations of $H_2$, CO, $CH_4$, and $CO_2$ are about 20.96%, 20.53%, 3.2% and 7.62%, and the net calorific value of fuel gas is 6.01 $MJ/Nm^3$. For case D, the average volume concentrations of $H_2$, CO, $CH_4$, and $CO_2$ are about 20.75%, 20.08%, 3.0% and 7.83%, the net calorific value of fuel gas is 5.86 $MJ/Nm^3$. Both case C and case D can achieve long-term stable operation. By comparison, case C shows better gasification performance due to its higher cold gas efficiency and carbon conversion.

A clean fuel gas production capacity of 60000 $Nm^3/h$ CFB coal gasification system was built in Hebei of China in Aug. 2015. The user is Jiujiang Jiaohua. The produced fuel gas was used to provide heat for coking, which replaced coke oven gas of the original process. The saved coke oven gas was used to produce liquefied natural gas. With the increase in production capacity, new key technologies were used in the whole system. For example, different from the previous single cyclone, two cyclones were arranged in parallel for this system. The outline of the industrial plant is shown in Fig. 2(c). At near full load, the fuel flexibility was evaluated. For case E, Shuozhou lignite coal was used as feedstock, the gasification temperature is about 950 ºC, and the fuel gas production is about 110% of the full load. For case F, Nuojin lignite coal was used as feedstock, the gasification temperature is about 951 ºC, and the fuel gas production is about 107% of the full load. The cold gas efficiency and carbon conversion of case E are higher than case F. These results are attributed to the higher gasification reactivity of Shuozhou. However, the net calorific values for fuel gas of case E is lower than case F, which is mainly due to the lower carbon content in raw coal. The fuel flexibility investigation indicates that both Shuozhou coal and Nuojin coal can achieve stable operation and can meet the production requirements.

As illustrated in Fig.3, for cases A to F, the cold gas efficiency ranges from 63.33% to 77.31%, the carbon conversion ranges from 80.33% to 87.42%, and the net calorific value of fuel gas ranges from 5.23 to 6.01 MJ/Nm$^3$. No matter the coal types and scale of gasifier, the gasification performances are satisfied and the produced fuel gas can meet the production requirements of the subsequent process. In addition, the fuel gas production can be easily tubed from 50% to 110% of the full load. The industrial applications show that CFB gasification is an efficient and clean coal conversion technology, with wide fuel flexibility, simple flow process and high social recognition.


Fig.2 Pictures of industrial CFB gasifier: (a) 25000 Nm$^3$/h hot flue gas production (Jiangsu Huiran); (b) 40000 Nm$^3$/h cold flue gas production (Xinfa huayu-stage I); (c) 60000 Nm$^3$/h cold flue gas production (Jiujiang jiaohua)

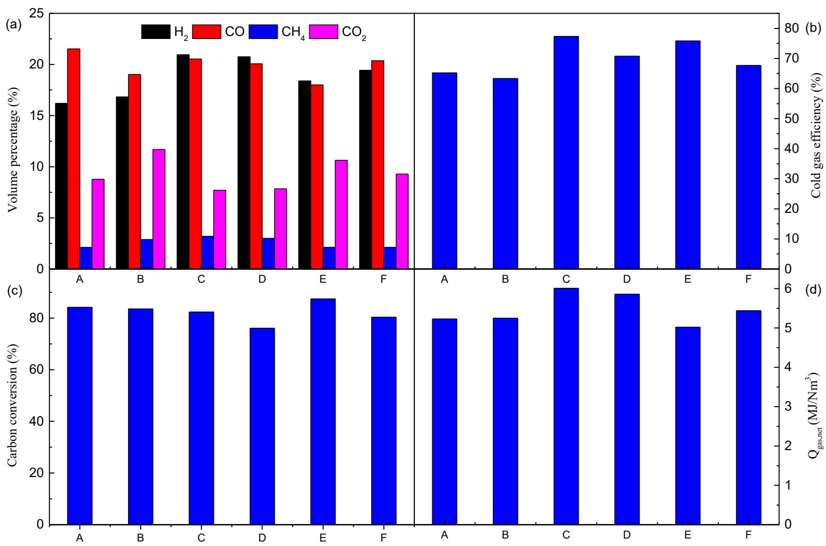


Fig.3 gasification performances of different cases investigated in this study: (a) volume percentage of fuel gas; (b) cold gas efficiency, (c) carbon conversion and (d) low heat value.

## CONCLUSION

CFB gasification is one of the key conversion technologies for the high efficiency and clean use of coal resources. Novel CFB gasification system has been developed by Institute of Engineering Thermophysics and achieved industrial application. Some novel key technologies were used in this system, such as counter-current air cap, air preheating technology, direct slag disposal technology, multi-stage self-balanced char transporting technology, and so on.

The effects of coal types, fuel gas production capacity and the output percentage of the full load were studied. The cold gas efficiency ranges from 63.33% to 77.31%, the carbon conversion ranges from 80.33% to 87.42%, and the net calorific value of fuel gas ranges from 5.23 to 6.01 MJ/Nm$^3$. In addition, the fuel gas production can be easily tubed from 50% to 110% of the full load. The produced fuel gas can meet the production requirements of the subsequent process. The results indicate that CFB gasification is an efficient and clean coal conversion technology, with wide fuel flexibility, simple flow process and high social recognition.

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