Applying carbon capture and storage to a Chinese steel plant

Feasibility Study on a CCS Facility for Shougang Jingtang United Iron & Steel Company's Caofeidian Steel Plant, China

Prepared for Global Carbon Capture and Storage Institute Ltd
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1. General Background of the Project

1.1 Overview of the Project

At around 2007, China surpassed the U.S. in its volume of CO_2 emissions, and since then, still keeps this position of being the first. Thus, CO_2 Emissions from China remains a significant and substantial issue.

This report is a result of a feasibility study on “Application of Carbon Capture and Storage Facility onto Shougang Jingtang iron & Steel Company’s Caofeidian Steel Plant in China”. It covers the concept of capturing CO_2 from a Chinese steel plant, to transport it and to store it potentially in an oilfield for EOR.

China, a major CO_2 emitting country, is also known as the largest iron making country in the world, dominating nearly half of the world’s production. From iron plants, enormous amount of CO_2 is released when reducing the iron ore with cokes. Therefore, its effect to global climate is significantly large. Considering this context, specific gases from the iron plant are highlighted and featured in this report.

At the same time, China is a vastly large country with widely spread oil and gas field. This presents a promise for possible utilization of the captured CO_2 in EOR or EGR applications. Thanks to locating some oilfield near the Caofeidian Steel Plant, the feasibility study on the integration from capturing to storage can be fascinated.

In this background, Toshiba, Tongfang Environment and Shougang Jingtang have been in consultation to study possible application of CCS technology onto a steel plant in China.

The project will find its uniqueness in the following points;

Uniqueness #1: The subject of the study is in steel works. Despite the wide array of CCS projects in the power generation arena, comparatively less project is found in the industry sector, including the field of Steel Works. The study can help shed more light on this arena.

Uniqueness #2: The project is located in China. As illustrated in GCCSI’s “Global Status of CCS” reports, we find that China is a fast-mover in terms of new CCS projects entering the pipeline with emphasis on its usage of the captured CO_2 such as EOR. This drive in China is relatively stronger compared to other stagnant regions.

Uniqueness #3: The project is about global collaboration. The goal of GCCSI is to foster knowledge sharing and networking on CCS globally, to bring the players together, gathering their strengths to drive CCS forward. This report is a fruit of collaboration of Japanese company with Chinese customer funded and supported by GCCSI. It is also worthy to note that, this feasibility study was authorized as one of the 41 collaboration projects in “the Japan China Business Alliance for Energy Saving and Environmental Protection” supported by Japanese and Chinese governments in December of 2014.

The global warming is now one of the hottest topics in the world in recent years. The object of this feasibility study is to understand the general system that can be designed to capture CO_2 from a steel plant, and to store it underground. In the process of doing this, the study aims to shed light on the issues before executing the real project.

The feasibility study is a product of the following key players:

Key Player #1: Shougang Jingtang (the customer)

Due to environmental issues imposed by the Beijing Olympic games in 2008, Shougang Jingtang Iron & Steel, who are ranked 6th in China and 9th in the world in production volume in 2013, relocated its Shijingshan Steel Plant formerly situated in the Beijing metropolitan area, to Caofeidian Steel Plant site approximately 200 kilometers away on the coastal area. This state-of-the-art steel plant accounts to quarter of the Group's production.

Shougang Jingtang had been intent in finding ways to capture CO_2 at the Caofeidian Steel Plant and possibly utilize it for EOR at oilfields nearby.

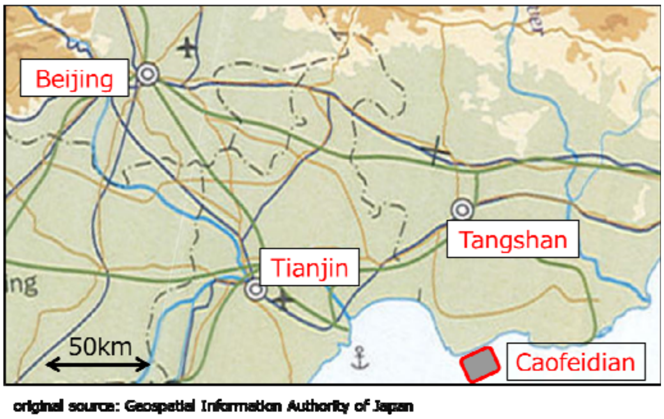

Fig. 1.1.1 Location of the Caofeidian Steel Plant

Key Player #2: Tongfang Environment

Tongfang Environment Co. Ltd of the Tsinghua Tongfang Group, working with Shougang Jingtang in providing their air quality control systems, learnt of Toshiba Corporation's CO_2 capture technology being demonstrated at its pilot plant in Mikawa thermal power plant, and asked for its support in provision of the CO_2 capture systems for Steel Works.

Key Player #3: Toshiba Corporation

Toshiba's general activity in CCS is later described in more detail in chapter 3.3.

For this project, Toshiba has been consulted by Shougang Jingtang United Iron & Steel of China, through our business partner Tongfang Environment, regarding possible application of CCS onto their Caofeidian steel plant.

1.2 Scope of Works

The project is driven by strong interests of Shougang Jingtang United Iron & Steel.

Its aim is to apply post combustion carbon capture technology onto an existing steel works in China, with off-take of CO_2 planned for EOR at nearby oilfield.

As depicted below, steel works is a heavily interlinked process of gases and byproducts.

Simplified Iron and Steel Making Process Schematic

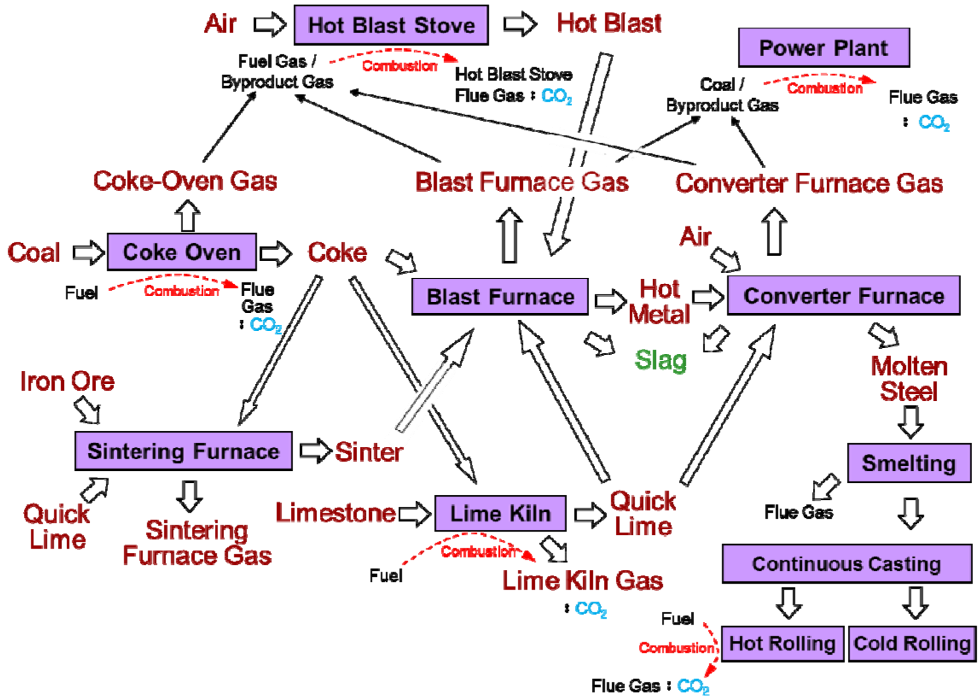

Fig.1.2.1 Iron and steel making process schematic

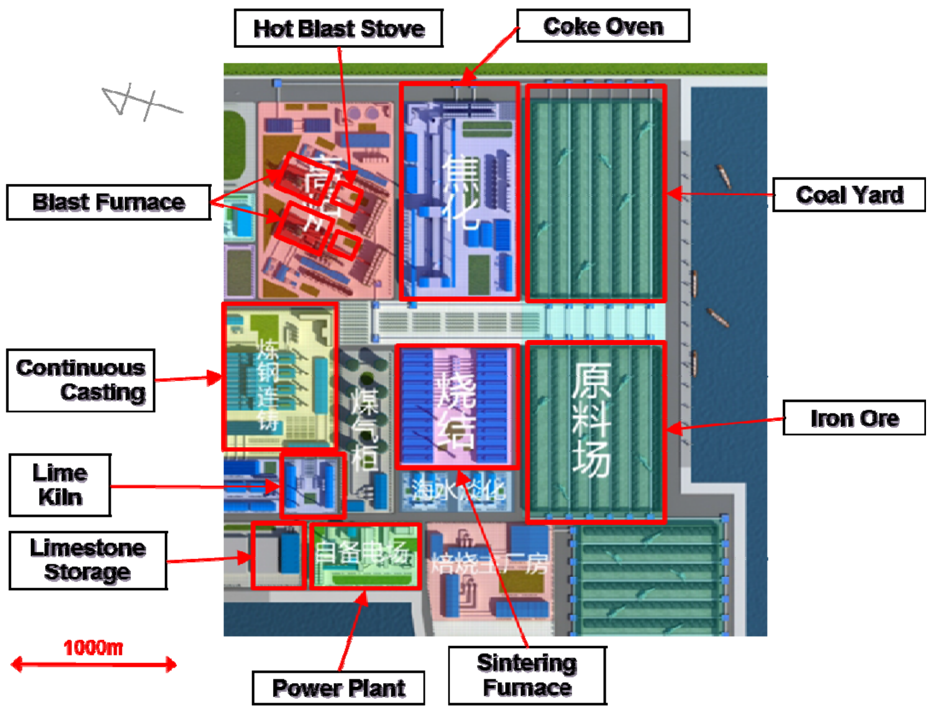

Fig. 1.2.2 Bird-eye view of Caofeidian steel plant

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The project will look for and match the waste heat sources in steel production which could be used to capture the identified CO_2 emissions via amine based chemical absorption CO_2 capture technology. In doing this, the project will verify the location and volume of emissions and heat sources in question, so that the proposed plant is viable both technically and physically.

1.3 Organization of the Project

Following are the partners and parties involved in this project, and their roles.

(1) Shougang Jingtang United Iron & Steel Company (Shougang Jingtang)

- Owner of the Caofeidian Steel Plant.
- Support and recognition of this feasibility study activity.
- Provision of Caofeidian Steel Plant data required to engineer and evaluate project.

(2) Toshiba International Corp Pty Ltd (TIC):

- Australian representation of Toshiba Corporation with its office in Sydney, Australia.
- Act as the contracting body with GCCSI in Canberra.

(3) Toshiba Corporation (Toshiba)

- Wrap and provide feasibility study report.
- Act as the contact point with GCCSI, in close collaboration with TIC.
- Coordinate activities and execute the feasibility study.
- CO_2 capture plant basic design and engineering.
- CO_2 capture performance test.

(4) Toshiba (China) Co. Ltd (TCH):

- Chinese representation of Toshiba Corporation with its office in Beijing, China.
- Provide overall support in Toshiba Corporation's work related to the project in China

(5) Tongfang Environment Co. Ltd (Tongfang)

- CO_2 capture plant detailed engineering based on Toshiba basic design.
- Costing and estimation of project facilities.

(6) Jidong Oilfield

- Provision of jidong Oilfield data required to engineer and evaluate project.

(7) Relationship

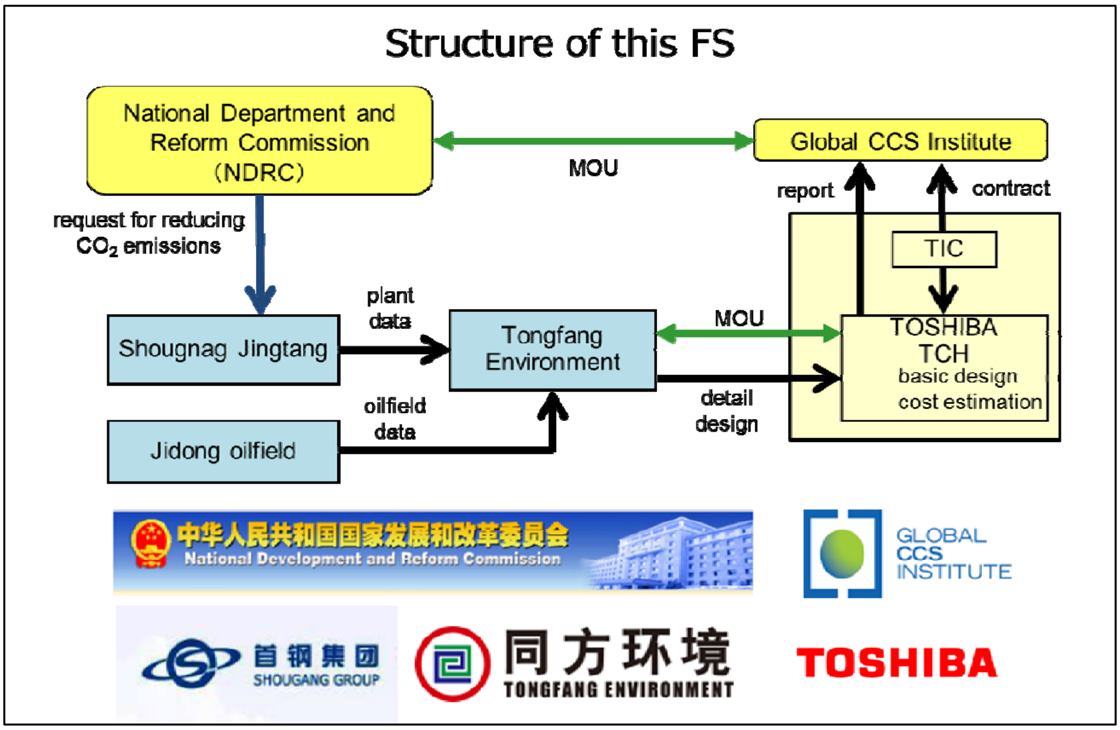

Fig.1.3.1 Structure of this FS

2. Overview of the Chinese Steel Industry

In view of characteristics of China, Toshiba outsourced survey work to a research company in China. The data utilized in this clause is based on the results surveyed by Crediteyes Co., Ltd., Toshiba normalized some of the data when in necessary and drew diagrams of the data.

2.1 CO_2 emissions from Chinese iron & steel industry

2.1.1 CO_2 emissions from China

According to statistics, the countries that passed the phase of the industrial revolution have started to emit large amounts of CO_2 since 1850. Carbon dioxide emissions of Great Britain, largest CO_2 emitter at the time, was six times as that of the United States, who held second largest volume of CO_2 emission. With unceasing development of global human civilization and deepening of industrialization process of the countries, the global CO_2 emission load has increased rapidly since 1960s. The carbon dioxide emissions in Asia had become the largest in 1990s. According to authoritative research institutions in the world, China's CO_2 emission accounts for 28%[1] of the total global emission and the annual emission has up to 10 billion tons[1], exceeding the sum of that of the United States and the European Union.

Now, China has become the most CO_2 emitting country in the world.

Fig. 2.1.1 describes the global carbon emissions in 2013. The emissions of China are 28% of the global total carbon emissions, while that of USA is 14% and EU is 10%[1].

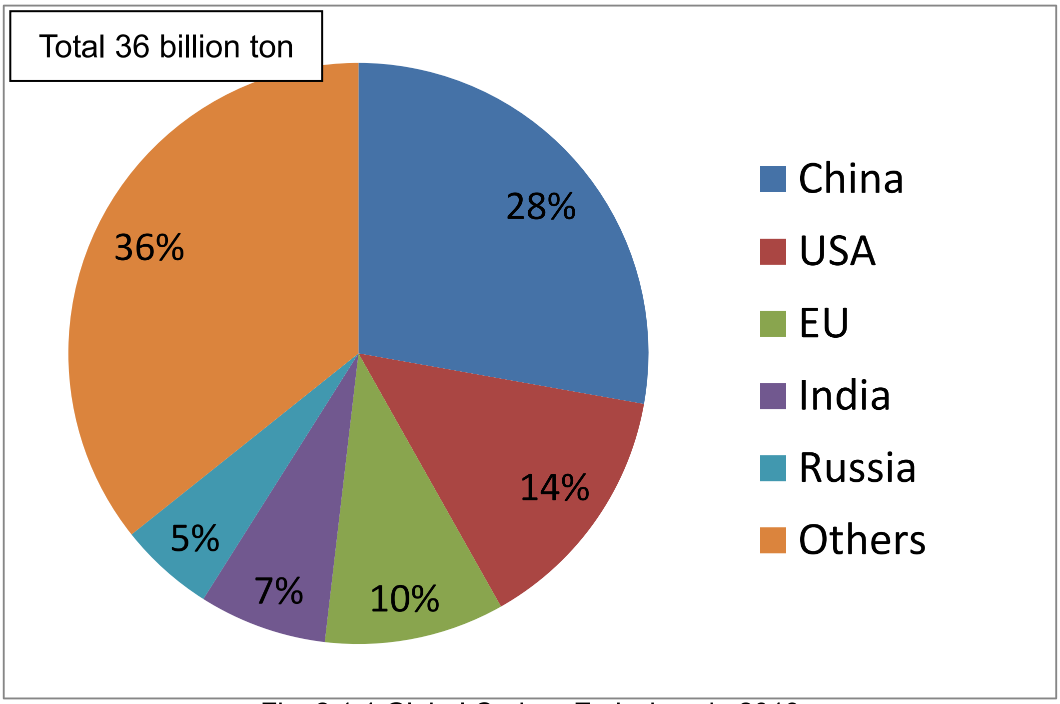

Fig. 2.1.1 Global Carbon Emissions in 2013

2.1.2 CO_2 emissions from Chinese steel industry

Fig. 2.1.2 shows that Chinese CO_2 emission was in a rising trend from 2005 to 2013. The figure in 2005 was 5.9 billion tons, and in 2012, CO_2 emission was at its highest with 10.3 billion tons. The average annual growth of emissions was over 500 million tons, and as a result, China has become the largest CO_2 emission country.

The CO_2 emission in 2013 decreased for the first time. The amount decreased nearly 300 million tons compared to that of 2012.

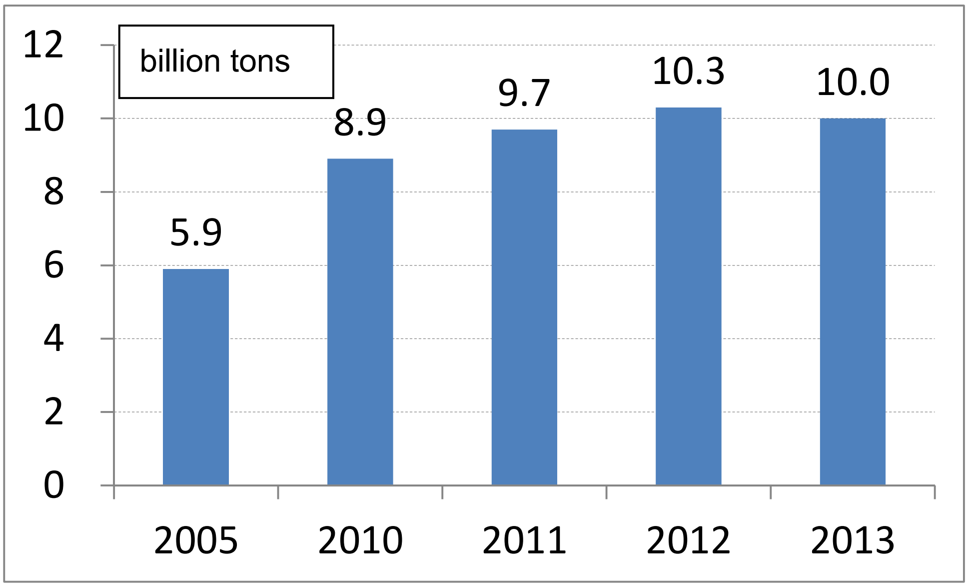

Fig. 2.1.2 Chinese CO_2 Emission Data in 2005, 2010, 2011, 2012, 2013

Despite the decrease in 2013, experts predict that CO_2 emission will still show increasing trend exceeding 11.5 billion tons until 2020, in the background of sustained and rapid economic development in China.

At present, there is no unified standard for carbon investigation in China. Different industries adopt different standards. There are various carbon emissions statistical standards which cross and cover many industrial sectors.

Power industry is a basic industry which supports the Chinese national economy. As shown in Fig. 2.1.3, huge power demand makes power industry the sector with the largest carbon emission. In 2013, carbon emission from power industry accounted for 38% of Chinese total carbon emission. This is followed by the cement industry which accounts for 23%, transport 21%, Steel 15%, Electrolytic Aluminum 2%, and Synthetic ammonia 1%.

In 2010, the global steel industry CO_2 emissions accounted for 6.7 % of total global CO_2 emission, while Chinese iron and steel industry accounted for 12% of total Chinese CO_2 emissions. However, in 2013, this has risen to 15%. The electricity for electrolytic aluminum production comes from thermal power, resulting in large volume of CO_2 emissions from electrolytic processes and aluminum production. Synthesis ammonia is one of the important inorganic chemical products and due to the high activation energy of synthesis ammonia, it consumes large amounts of energy and emits large volume of CO_2 in preparation of the feed gas.

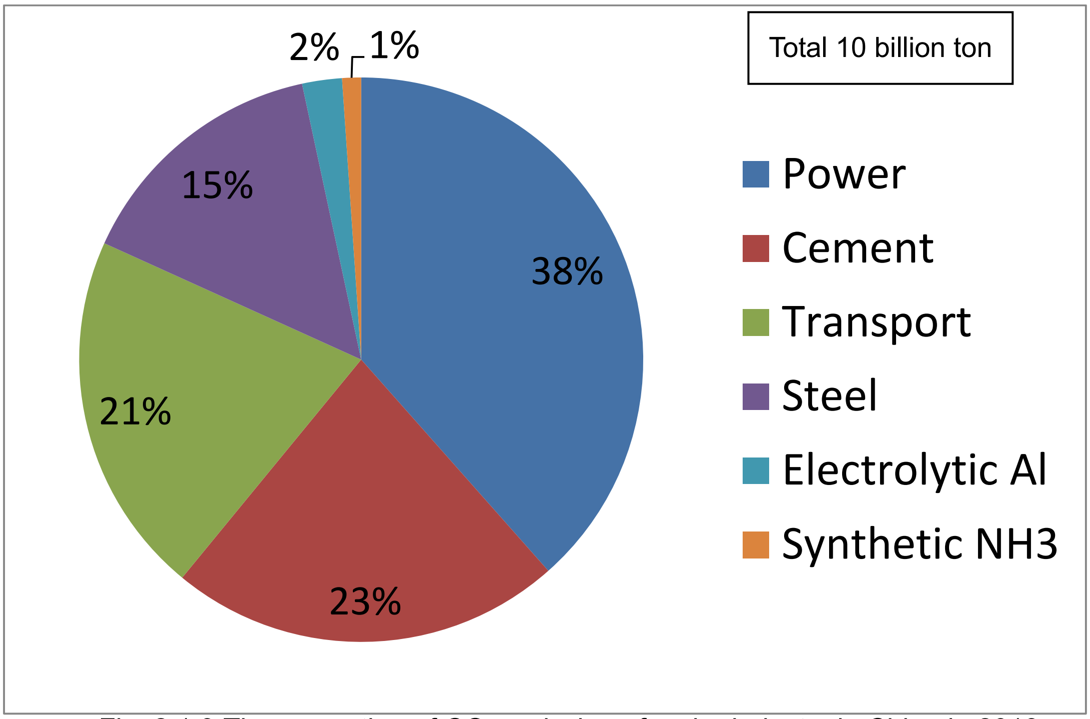

Fig. 2.1.3 The proportion of CO_2 emission of major industry in China in 2013

2.1.3 CO_2 emission share within the Chinese iron & Steel Industry

Steel Industry Production

According to Fig. 2.1.4, China's steel industrial crude steel output has been increasing year by year in the last 10 years. Crude steel output is 350 million tons in 2005. In 2013, even with somewhat stagnant industry status, the output still increases by 60 million tons to 780 million tons in total, with the growth rate at 7.6%, the highest in recent years.

There are great number of iron & steel companies in China. The production of crude steel by the top ten enterprises accounts to 307 million tons, which occupy 40% of all the production output.

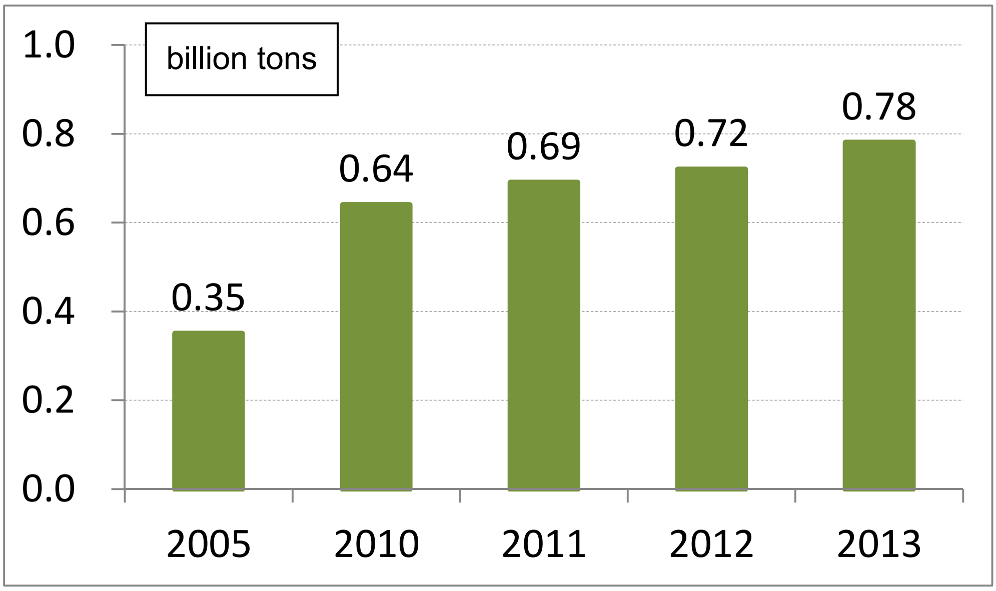

Fig.2.1.4 China's Crude Steel Production

CO_2 emissions

In accordance with the annual growth of the steel industry, Fig. 2.1.5 shows that during the period of 2005-2013, total carbon dioxide emissions of China's steel industry grew stably and steadily. In 2005, carbon dioxide emissions of nationwide steel industry was 0.78 billion tons, while in 2010, five years later, it has risen to 1.29 billion tons. In 2013, although the whole steel industry was not in boom, crude steel production still had certain growth, with a corresponding slight growth in carbon dioxide emissions reaching 1.5 billion tons. The overall energy conservation and emission reduction trend limited the growth rate to only 3.0 %.

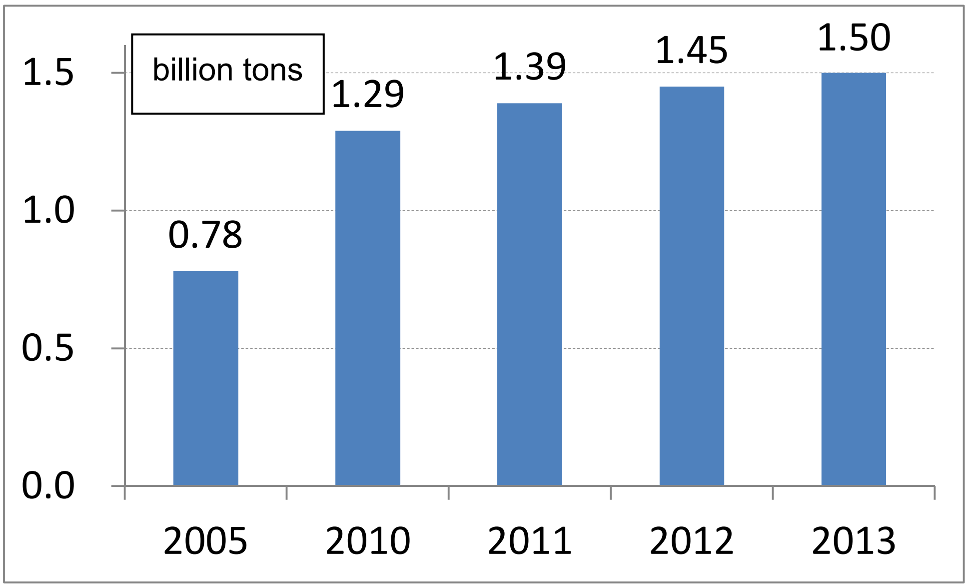

Fig.2.1.5 CO_2 Emissions of Chinese Steel Industry in 2005, 2010, 2011, 2012, 2013

Domestic iron and steel enterprises in the last ten years, have realized energy conservation in the industry. Therefore, many iron and steel groups have begun to implement energy conservation measures from 2004. The main emphasis of this measure is, utilizing new technologies and new management mode to reduce coal usage, storage or reusing of waste heat and waste energy effectively, and reaching ideal goal of steelmaking with minus energy consumption.

The total carbon emissions by the top 10 enterprises are 600 million tons, which accounts to 40% of the total carbon emissions from the entire iron and steel industry. The largest is Hebei Iron & Steel accounting to 5.8%. The second largest is Baosteel with 5.7%. Shougang Gr. is the 6^{th} largest company with 4.2% share.

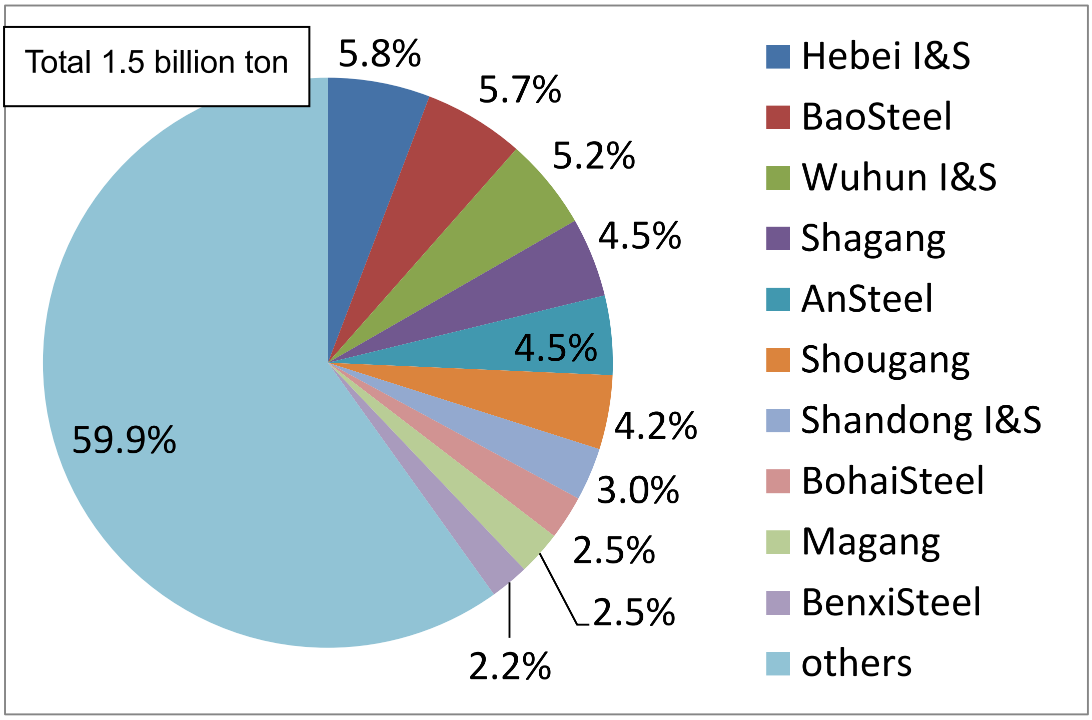

Fig. 2.1.6 The Carbon Emissions Proportion of the Top Ten Enterprises of China's iron and Steel Industry in 2013

2.1.4 Policies for CO_2 emissions reduction in Chinese iron & Steel Industry

Kyoto Protocol formally took effect in 2005 with CDM as core market mechanism for CO_2 emission reduction. Meanwhile, developed countries began to start carbon trading mechanism. As a developing country, China did not assume carbon emission reduction obligation from 2008 to 2012, while some enterprises have obtained emission reduction profit via cooperation with international organizations.

Up to now, Chinese government has not yet separately promulgated national unified carbon reduction policies and regulations. Generally speaking, measures for energy conservation and emission reduction have limited or reduce carbon emission to some extent.

In 2012, scheme for greenhouse gas emission in Twelfth Five-year Plan proposed that CO_2 emission of gross domestic product in 2015 shall be reduced 17% compared with that of 2010. It was stipulated that energy-saving and cost-reducing shall be vigorously carried out, energy structure shall be optimized, carbon sink shall be increased, industrial system and lifestyle with low-carbon feature shall be formed.

In 2014, U.S.-China Joint Announcement on Climate Change proposed that the United States intend to achieve an economy-wide target of reducing its emissions by 26%-28% below its 2005 level in 2025. On the other hand, China intend to achieve the peaking of CO_2 emissions around 2030 and to make best efforts to bring this peak earlier and also intend to increase the share of non-fossil fuels in its primary energy consumption to around 20% by 2030.

For Iron and steel industry, the state has clear restrictions on Industrial waste gas in recent years. Limit imposed on carbon emissions is not yet clear, but with the accelerated process of national carbon trading, corporate carbon quota allocation, CO_2 gas will be considered as part of this limitation by the enterprise industry

2.2 General Description of Shougang Jingtang

2.2.1 History

Shougang Group was originally founded in 1919.

In February 2005, the state council approved Shougang to implement capacity reduction, relocation, structure adjustment and environmental management plan, and agreed to build an integrated iron and steel enterprise with internationally advanced technology. The plant was relocated to Caofeidian, Tangshan, Hebei Province. On June 5, 2005, the production from the former old furnaces ceased, when the relocation work started officially.

By the end of 2010, main process of former old Shougang Beijing Shijingshan Steel fully stopped production and operation of the second step of Phase 1 engineering of Caofeidian Shougang Jingtang Iron and Steel Company commenced. The newly built blast furnace of Shougang Jingtang Plant with 5,500 cubic meters capacity went into operation, and this became the largest and most advanced technology blast furnace in China that year.

Table 2.2.1 Shougang Group's Development history

Year	History
1919	Shougang Group was founded
1999	Set up Beijing Shougang Company Limited
2005	Set up Shougang Jingtang United Iron & Steel Co., Ltd. with the cooperation of Tang Gang Huayye (Tianjin) Steel Marketing Co., Ltd Purchased Guizhou Shuigang

	National Development and Reform Commission officially replied the program that Shougang relocate to Caofeidian
2009	Purchased Shanxi Changzhi Iron ＆Steel Group
2010	Shougang finished its relocation

2.2.2 Iron Production

In 2005, when the relocation from Beijing to Caofeidian started, Shougang Group's crude steel output totaled 10.44 million tons. After completing the relocation, Shougang significantly increased the output of crude steel up to 31 million tons in 2010.

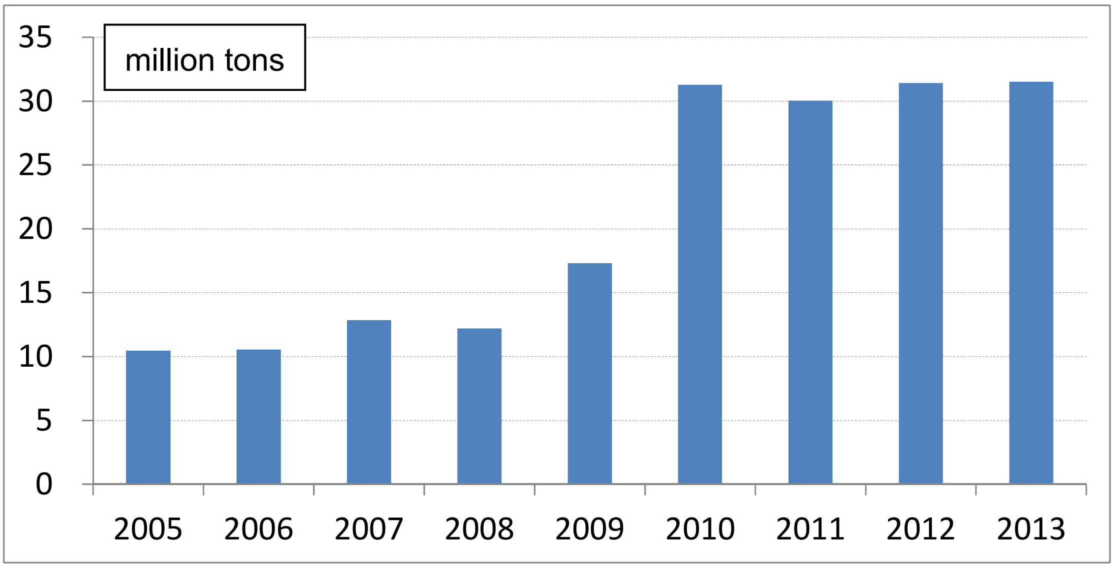

Fig. 2.2.1 Crude Steel Production of Beijing Shougang Company Limited from 2005 to 2013

2.2.3 CO2 emissions

CO_2 emissions from Shougang Group was 22.58 million tons in 2005. It rose to 64.44 million tons in 2010, and it fell to 60.68 million tons in 2011. With the recovery of growth of production, carbon emissions grew again to 61.52 million tons in 2013.

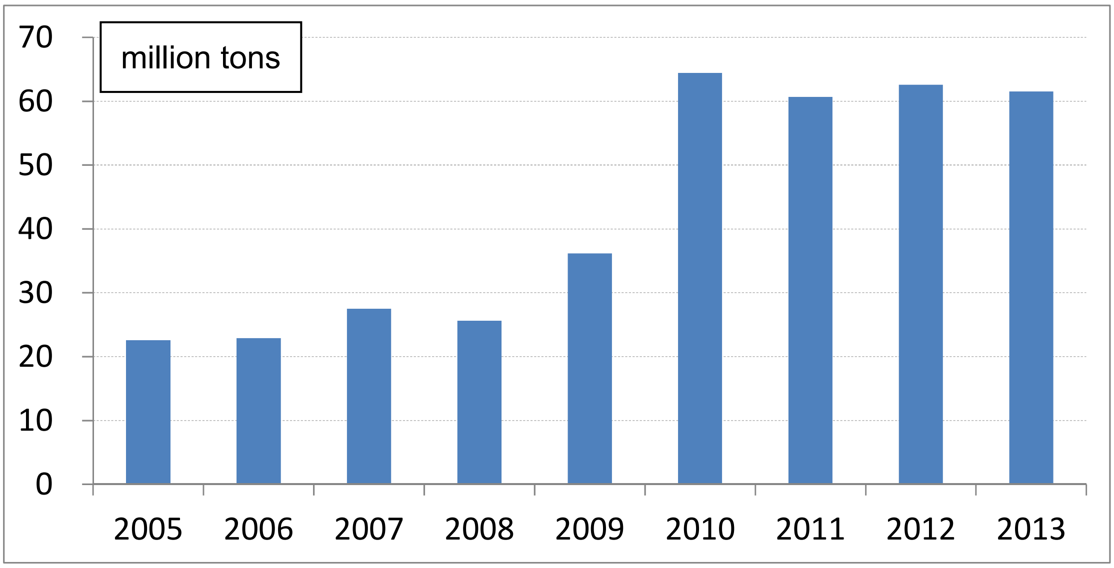

Fig. 2.2.2 CO_2 Emissions of Beijing Shougang Company Limited from 2005 to 2013

The amount of CO_2 emissions from Caofeidian Steel Plant itself is not clear so far. Roughly estimating that the mass of CO_2 emissions is twice the production of crude steel, in 2013 Caofeidian Steel Plant would have emitted about 16 million tons of CO_2, when it was producing about 8 million tons of crude steel.

CO_2 capture and storage work in iron and steel plants has just started in China. Currently, Shougang Jingtang Caofeidian Steel Plant has no CO_2 emissions data, so they are in the process of collecting statistics of these data for each process now. Future CO_2 reduction target of Shougang is 1,000,000 t/y. The target is based on the company policy rather than requirements of NDRC and the state.

2.2.4 Measures for reducing CO_2 emissions

There are mainly two measures to reduce CO_2 emission in iron and steel industry. First is to reduce CO_2 and other greenhouse gas emissions in source via energy conservation and emission reduction through improvement of the production process. Second is to conduct back-end technical processing of CO_2 emissions to achieve objective of reducing emission.

2.2.4.1 Energy Conservation and Emission Reduction

Energy-saving and cost-reducing is usually the most direct method to reduce CO_2 emission in iron and steel producers.

Here, iron and steel enterprises calculate and report all CO_2 emissions produced by all the equipment and business, including direct production system, auxiliary production systems (such as power, electricity, water, etc.) as well as affiliated production system serving the production (such as canteens, fleet, workshops bathroom and so on).

The main direct CO_2 emissions equipment includes sintering machine, coke oven, dry quenching furnace, blast furnace, converter, continuous casting machine, rolling mill, shaft kiln and rotary kiln, power generation boiler, etc.

After the completion of the relocation, Shougang Group began a top-down work on energy conservation and emissions reduction. Shougang Group started consultation and negotiation with domestic and foreign industry technology partners concerning carbon emissions control, and have then implemented several saving energy and waste heat recovery projects.

Table 2.2.2 shows some of the examples of the technical cooperation projects on energy conservation and emissions reduction at Shougang Company.

Table 2.2.2 Shougang's Carbon Emission Technical Cooperation Information

Technical Partner	Project Brief
Nippon Steel & Sumitomo Metal Corporation	Tangshan Caofeidian Steel Plant Waste Heat Recovery Project
Mitsubishi Corporation	China Qianan Steel Factory Blast Furnace WASTE Gas WASTE Pressure Recovery Project
Nippon Steel & Sumitomo Metal Corporation	Use of large 260 t/h dry quenching equipment supporting large coke oven in Shougang Jingtang Steel Factory

The overall benefit of energy saving became obvious when CO_2 emissions fell from 64.44 million tons in 2010, down to 60.68 million tons in 2011. With the growth of production, however, carbon emissions grew again to 61.52 million tons in 2013.

2.2.4.2 Carbon Emissions Back-end Measures

Carbon emissions back-end processing measures mainly refer to the carbon recycle/carbon capture technology. Now the major technologies include physical absorption, chemical absorption, adsorption, membrane, cryogenic distillation, etc. Caofeidian Steel

Plant has willingly started to explore this concept, but has not yet started capturing CO_2 from their plant.

This feasibility study has been conducted to investigate the practicalities of CO_2 reduction through implementation of the back-end measures..

3. CO_2 Capture Plant planning

3.1 Overview of Caofeidian Iron & steel plant

3.1.1 Caofeidian Iron and Steel processes

Caofeidian iron & steel plant is located in Caofeidian New District, Tangshan City, Hebei Province, 220 km away from Beijing in the west, and 80 km away from Tangshan City in the North. Caofeidian has a 25m deep-water harbor. The harbor never freezes and silts, therefore, it is the deep-water port having the optimal conditions in northern China. In phase-I steel project of Shougang Jingtang, the design annual iron output is 8.98 million tons, steel output is 9.7 million tons and steel products output is 9.13 million tons.

The construction commenced on March 12, 2007, and the No.1 5500m3 blast furnace was blown in and ignited to produce iron on May 21, 2009, then steelmaking, hot rolling and cold rolling have been put into production successively, the steel plant has been fully completed through only one step. On June 26, 2010, Shougang Jingtang Phase-I project has been completed and put into production. Shougang Jingtang's product positioning is the high-end fine boards, iron and steel products are mainly divided into hot-rolled and cold-rolled ones.

Caofeidian iron & steel plant's process flow diagram is shown in Fig.3.1.1 as below;

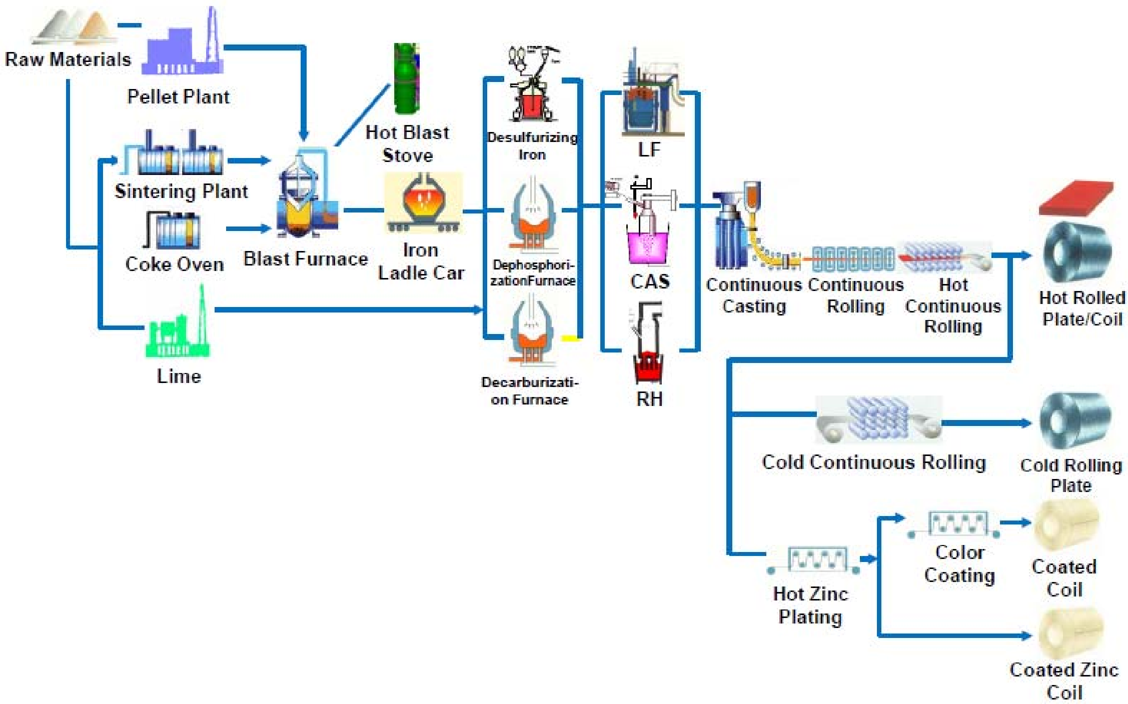

Fig.3.1.1 Process flow at Caofeidian iron & steel plant

Main process equipment of Caofeidian iron and steel plant includes four 7.63m coke ovens and supporting dry quenching facilities, two 550m^2 sintering furnaces, one 504m^2 pellet belt-type roasting machine, two 5500m^3 blast furnaces, two 300t dephosphorization converters, three 300t decarburization converters, one Ladle Furnace (LF) refining furnace, two Composition Adjustment by Sealed Argon Bubbling (CAS) refining units, two Ruhrstahl-Heraeus (RH) vacuum refining units, two 2150 mm strand slab casters, two 1650 mm strand slab casters; 2250 mm and 1580 mm hot strip mill; 2230 mm, 1700 mm and 1420 mm Continuous Descaling and Cold-rolling Mill (CDCM) and supporting continuous annealing line, batch annealing, hot galvanizing, crosscutting unit production line and so on.

Two 5500m^3 blast furnaces have been independently designed by Beijing Shougang International Engineering Technology Co., Ltd.(BSIET) and constructed by Beijing Shougang Construction Group Co., Ltd.(SGCG), daily output of single furnace is up to 12,000 tons or more.

Caofeidian plant has six sets lime kilns, which are used for production of lime needed by steel mill. Kiln type is of shaft kiln.

In 1990s, Shougang Jingtang has firstly introduced German Beckenbach shaft kiln technology in the domestic metallurgical industry. In early 2000s, based on the lessons drawn from the original shaft Beckenbach shaft kiln technology, the original shaft kiln technology has been improved, and the new shaft kiln technology with Shougang Jingtang characteristics has been created. The improvements mainly concentrated on the full optimization of shaft kiln lining structure, introduction of Programmable Logic Controller (PLC) control systems that adaptive to shaft kiln process, etc.. In addition, it gradually became the homemade shaft kiln technology, and the optimized shaft kiln thermal system meets the requirements for use of 60mm or smaller limestone materials, and provides the converter shop “dehydration, degassing and deoiling” converter smelting with lump lime of smaller size to ensure a shorter smelting period of the converter production.

Shougang Jingtang’s shaft kiln main technological indexes: annual output of active lime is 496,800 t, light-burned dolomite is 165,600 t. Its supply of products includes converter steelmaking, Ladle Furnace (LF) refining, Kanbara Reactor (KR) molten iron desulphurization process, etc.

Shougang Jingtang 5500m^3 blast furnace is equipped with four sets of high blast temperature long-service-life hot blast stove. The design blast temperature is 1300℃, and dome temperature is 1420℃. High-temperature zone of the stove uses the silica bricks. Fuel of hot blast stove is single blast furnace fuel, using waste heat of the flue gas to recover the device’s preheat gas and combustion air, and equips two small top-combustion hot blast stoves to separately preheat the combustion air and make its temperature reach more than 520℃. Hot blast stove high-temperature valve uses the pure water closed circulation for cooling. Combustion, blowing-in and stove changing of the hot blast stove are of automatic control. When four hot blast stoves are working properly, use two-combustion and two-blowing-in interlaced parallel blowing-in mode, and in the case of the blast furnace gas is used as fuel, the blast temperature can reach 1300℃. In working conditions of three-combustion one-blowing-in and two-combustion one-blowing-in, the blast temperature can reach 1250℃.

3.1.2 Source of CO_2

There are several main streams having high concentration of CO_2 in them in a steel plant. The candidates of the streams for capturing CO_2 were proposed by Shougang Jingtang and are shown in Table 3.1.1. They are the gas streams from #4 lime kiln, #3&4 hot blast stove applying to #1 Blast furnace, Coke oven, Heating furnace, and thermal power plant of its own. The character of the streams in Caofeidian iron & steel plant has been estimated in order to decide which streams would be adequate for the CO_2 source in this study.

The table shows that the gas from the hot blast stove has the highest concentration of CO_2, 28.5%, and the next is the 19.3% gas from the lime kiln. In general, the more concentrated the CO_2 in the gas, the lower the recovery energy.

Considering the total amount of CO_2 emitted from each facility, the gas from the thermal power plant is the largest. If capturing CO_2 from the stream including the most CO_2 amount, the impact would be large.

In this feasibility study, two cases were carried out.

Firstly, Shougang Jingtang proposed us to target the gas from the lime kiln, and Toshiba took this into consideration as “Case 1”.

Secondly, Toshiba selected the most promising gas from the candidates in Table 3.1.1. Hot blast stove, which is one of the major and specific CO_2 sources of iron and steel industry, is also worth considering the application of Carbon capture and storage facility in view of both CO_2 concentration and annual emission. We call this “Case 2”.

Although the flue gas from the thermal power plant has the biggest amount of CO_2 emissions, Toshiba excluded this stream from the choices of CO_2 emission source, because it is not unique to the steel plants.

Table 3.1.1 Estimated CO_2 emissions

	Flow rate	Temp.	Conc.(CO_2)	CO_2 emission	
	m^3N /h	deg C	vol.%	t/d	kt/y
#4 Lime kiln	75,304	110	19.3	685	205
#3&4 Hot blast stove applying to #1 Blast furnace	369,420	258	28.5	4,967	1,490
Coke oven	800,000	210	11.0	4,024	1,207
Heating furnace	979,000	300	10.0	4,615	1,385
Thermal power plant of its own	2,600,000	20	9.9	12,135	3,640

3.1.3 Source of Heat for reboiler

A steel plant has a variety of hot streams in the system. A cutting-edge plant is so designed to be able to reuse the waste heat from these hot streams.

Similar to selecting the CO_2 source in clause 3.1.2, a source gas for heat needs also to be determined. The temperature of the gas stream was determined to be more than 155.9 deg C at least, because the steam for reboiler should be generated at 135.9 deg C.

The candidates of the streams for recovering heat were proposed by Shougang Jingtang and are shown in Table 3.1.2. They are the gas streams from #3&4 hot blast stove applying to #1 Blast furnace, Coke oven, #2250 Heating furnace, and #1580 Heating furnace.

The table shows that all the gases are high enough to reuse the heat. Naturally it is ideal to use hotter gases to recover the heat. Heating furnace's exhaust gas seems to be the best in the choices. However, because Shougang Jingtang had another plan for utilizing this heat source, we concluded to use hot blast stove's exhaust gas both in case 1 and 2.

Table 3.1.2 Estimated potential CO_2 recovery rate

	Flow rate	Temp.	Potential heat rate	Potential CO_2 recovery rate	
	m^3N /h	deg C	kJ/h	t/d	kt/y
#3&4 Hot blast stove applying to #1 Blast furnace	369,420	258	45,416,495	440	132
Coke oven	800,000	210	51,936,000	503	151

#2250 Heating furnace	628,000	300	108,593,760	1051	315
#1580 Heating furnace	351,000	300	60,694,920	587	176

3.1.4 Study cases

As for the demand of CO_2 at nearby oil field (Jidong oil field), preliminary information showed that the demand was approximately 300 tons of CO_2 per day, equivalent to 100 thousand tons per annum. Toshiba and Tongfang Environment set this amount for the target value of CO_2 capturing in this feasibility study.

The conditions of case 1 and 2 are shown in Table 3.1.3.

Table 3.1.3 Study cases

	CO_2 recovery rate	Flue gas as CO_2 source	Flue gas as heat source	CO_2 usage
Case1	0.1Mt/y (300t/d)	Lime kiln	Hot blast stove	EOR
Case2	0.1Mt/y (300t/d)	Hot blast stove	Hot blast stove	EOR

3.2 Overview of the CO_2 capture plant planning at Caofeidian steel plant

3.2.1 Plant overall description

The selection of a heat source and a CO_2 source were required in designing the CO_2 capture plant, using the flue gas of existing iron and steel industry. We planned it according to above-mentioned study cases. As for the Case1 and Case2, schematics of CO_2 capture plant applying to iron and steel plant are shown in Fig.3.2.1 and 3.2.2 respectively.

Case1:

Hot blast stove flue gas, which has a high temperature, is utilized as a heat source to make steam via steam generator, and this steam is supplied to the CO_2 capture plant.

At first, the gas is extracted from the duct between the hot blast stove and a stack, and all the gas cooled at the steam generator is returned to the downstream of the extracting point of the duct.

On the other hand, lime kiln gas, which has high CO_2 concentration, is supplied to the CO_2 capture plant as a CO_2 source. The gas is extracted from the duct between the lime kiln and a stack, and after a part of CO_2 containing in the extracted gas is removed at the absorber, the CO_2 depleted gas is returned to the duct to the hot blast stove's stack, which is the nearest stack from the CO_2 capture plant.

CO_2 is regenerated at the stripper by heating CO_2 rich solvent with steam made in the steam generator. The captured CO_2 is compressed at the compression facility, and transferred through an underground pipeline to the EOR site.

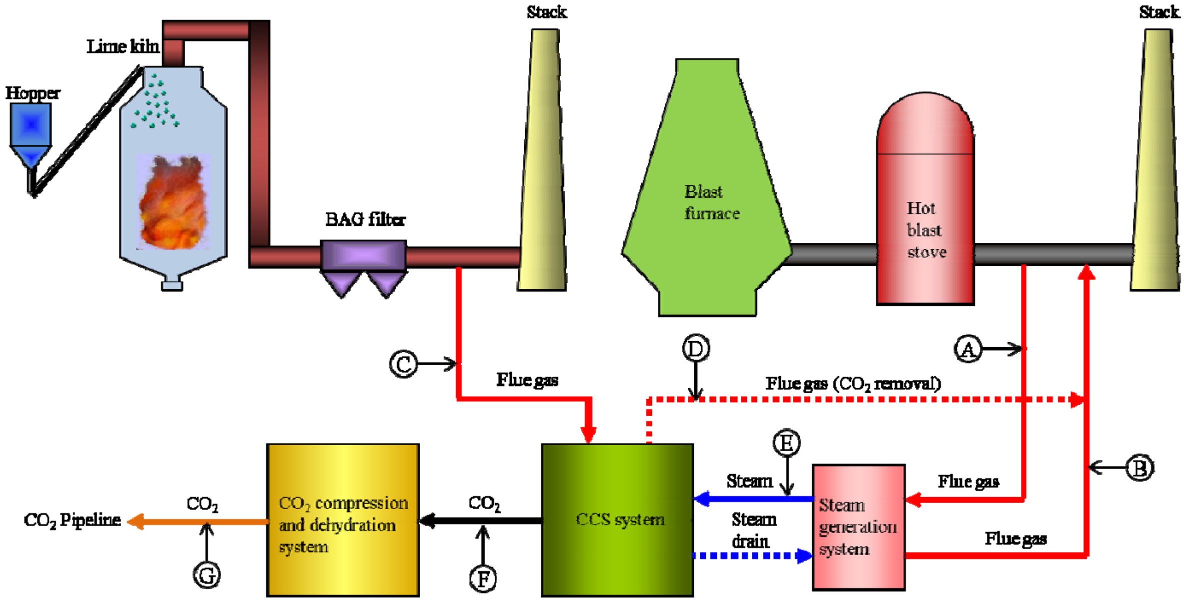

Fig.3.2.1 Schematic of CO_2 capture plant applying to iron & steel plant (Case1)

Case2:

Hot blast stove flue gas, which has a high temperature, is utilized as a heat source to make steam via steam generator, and this steam is supplied to the CO_2 capture plant.

At first, the gas is extracted from the duct between the hot blast stove and a stack, and part of the gas cooled at the steam generator is returned to the downstream of the extracting point of the duct.

On the other hand, the rest of the flue gas, which has high CO_2 concentration, is supplied to the CO_2 capture plant as a CO_2 source. After a part of CO_2 containing in the rest of flue gas is removed at the absorber, the CO_2 depleted gas is also returned to the downstream of the same duct to the stack.

CO_2 is regenerated at the stripper by heating CO_2 rich solvent with steam made in the steam generator. The captured CO_2 is compressed at the compression facility, and transferred through an underground pipeline to the EOR site.

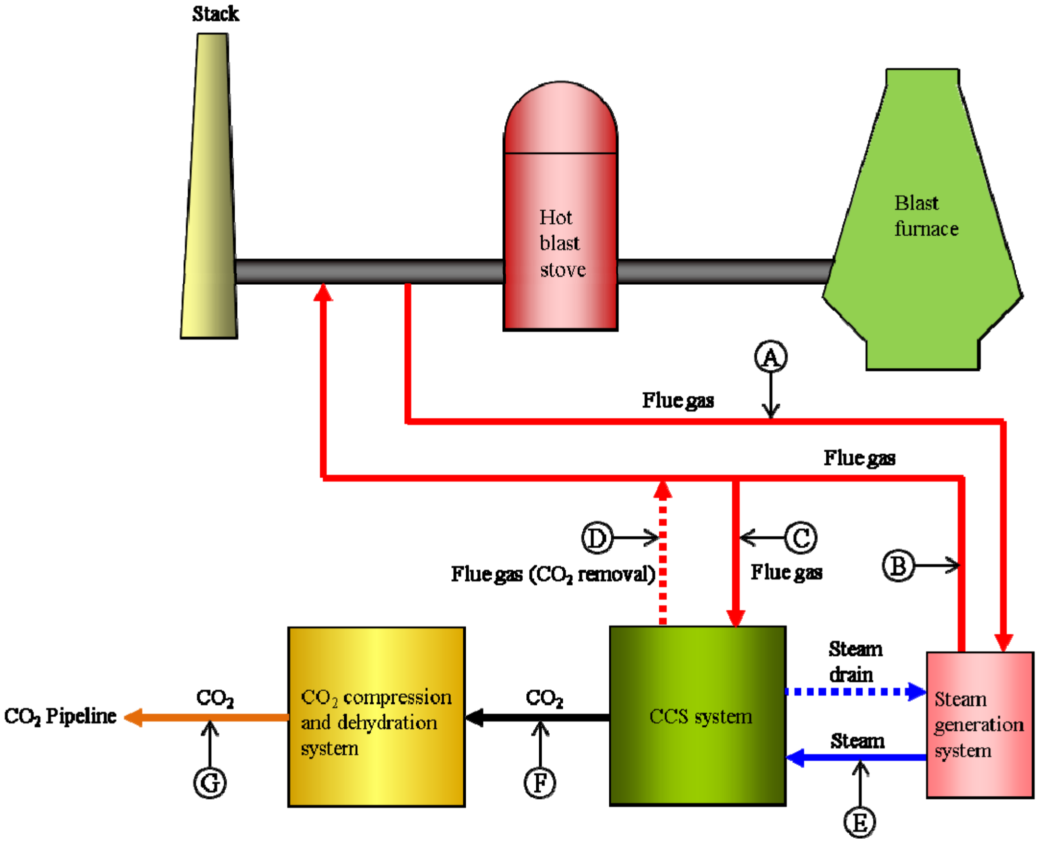

Fig.3.2.2 Schematic of CO_2 capture plant applying to iron & steel plant (Case2)

3.2.2 CO_2 capture plant description

Chemical absorption method, which uses amine-based solvent for CO_2 capture plant, was applied for this study. Schematic of this CO_2 capture method is shown in Fig.3.2.3.

When the lean solvent is fed from the top of the absorber tower, CO_2 in the flue gas is selectively absorbed into the solvent when it directly comes in contact with the gas supplied from the bottom of the tower. The CO_2 depleted gas is then emitted from the top of the absorber.

CO_2 rich solvent is supplied to the top of the stripper tower from the bottom of the absorber, after going through a heat exchanger. In the stripper, the rich solvent is heated in the reboiler by steam, and CO_2 is regenerated from the solvent in the stripper. The regenerated CO_2 is emitted from the top of the stripper tower. The regenerated solvent, which is now lean in CO_2, is supplied again from the bottom of the stripper tower to the top of the absorber tower after going through the heat exchanger and a cooler. The solvent circulates CO_2 absorption tower and regeneration tower.

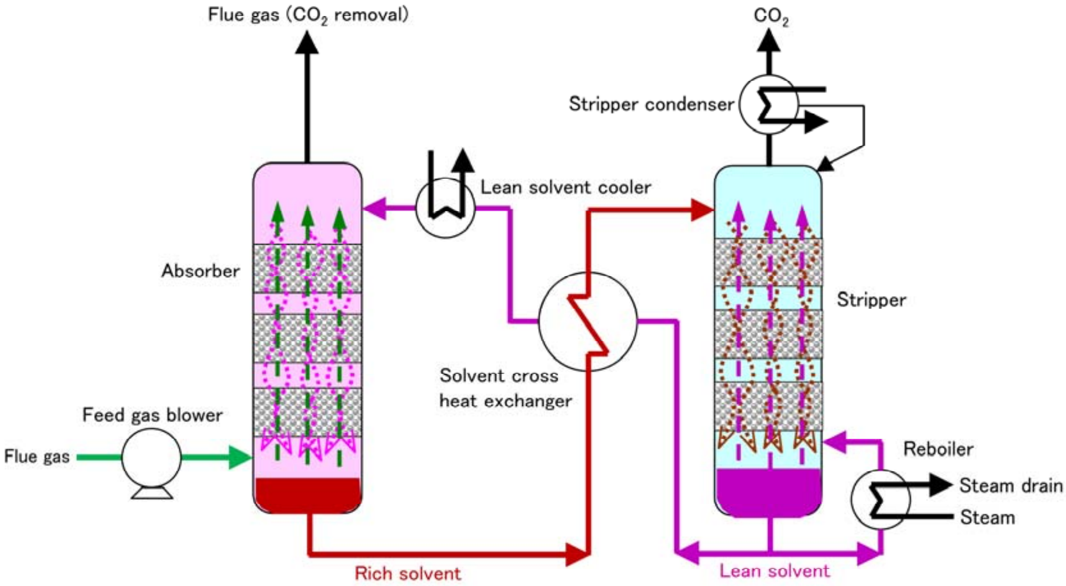

Fig.3.2.3 Schematic of CO_2 capture plant by chemical absorption method

3.3 Mikawa pilot plant modification and testing

3.3.1 Design of Mikawa pilot plant

With view to provide solution for global warming, Toshiba has been developing its post-combustion CO_2 capture technology since 2005. Considering the importance of verifying the technology when applied to real flue gas from a coal-fired power plant, Toshiba started designing and engineering a 10 t- CO_2 /d pilot plant from 2008. The plant was installed and commenced operation in 2009. The plant was specifically designed to connect to the Mikawa coal-fired power plant, which is located in Fukuoka, Japan. The Mikawa coal-fired power plant is owned by Sigma Power Ariake Co.,Ltd. a subsidiary of Toshiba.

In order to correctly plan the facility and evaluate the energy penalty incurred by application of CO_2 capture system to a power plant, Toshiba has been utilizing this Mikawa pilot plant extensively. The plant employs and operates on Toshiba's amine based chemical absorption post combustion capture technology. Since its operation, it has more than 8500 hours of operating experience to date, including 2800 hour continuous and stable operation. (Video: http://vimeo.com/62751266)

While the Mikawa plant is utilized to improve and verify the performance of the unit, it is also used to test for different plants and flue gas conditions. The flue gas from the coal-fired Mikawa power plant is a continuous flue gas containing 11 to 13 vol.% of CO_2 .

3.3.2 Modification of Mikawa pilot plant

In an amine based chemical absorption process, energy requirement (penalty) is known to largely depend on the concentration of CO_2 in the flue gas. Generally, the richer the concentration of CO_2 in a flue gas, the lesser the energy requirement.

As described in 3.3.1, the Mikawa plant was originally designed to test against flue gas of a coal-fired power plant. Toshiba has modified the piping system so that flue gases having a large rage of CO_2 concentration can also be examined using this same flue gas.

As depicted in Fig.3.3.1, the Mikawa plant has been fitted with a gas recirculation line connecting the top of the stripper tower to the absorber inlet, which enables the facility to enrich the CO_2 concentration of the incoming gas.

In the same way, these is also a gas recirculation line from the top of the absorber tower to the absorber inlet, giving the capability of the facility to dilute the CO_2 concentration of incoming gas to the absorber. Air bypass line is also equipped to the dilute CO_2, in case of enriching the O_2 concentration of the incoming gas.

With this modification, the plant is now capable of testing the technology on a simulated flue gas ranging from gas-fired power plant which contains about 4 vol.% of CO_2 or a blast furnace gas from steel plant which contains about 30 vol.%. (Note: This modification to Mikawa pilot plant was made by Toshiba, for purpose of supporting Toshiba's studies.)

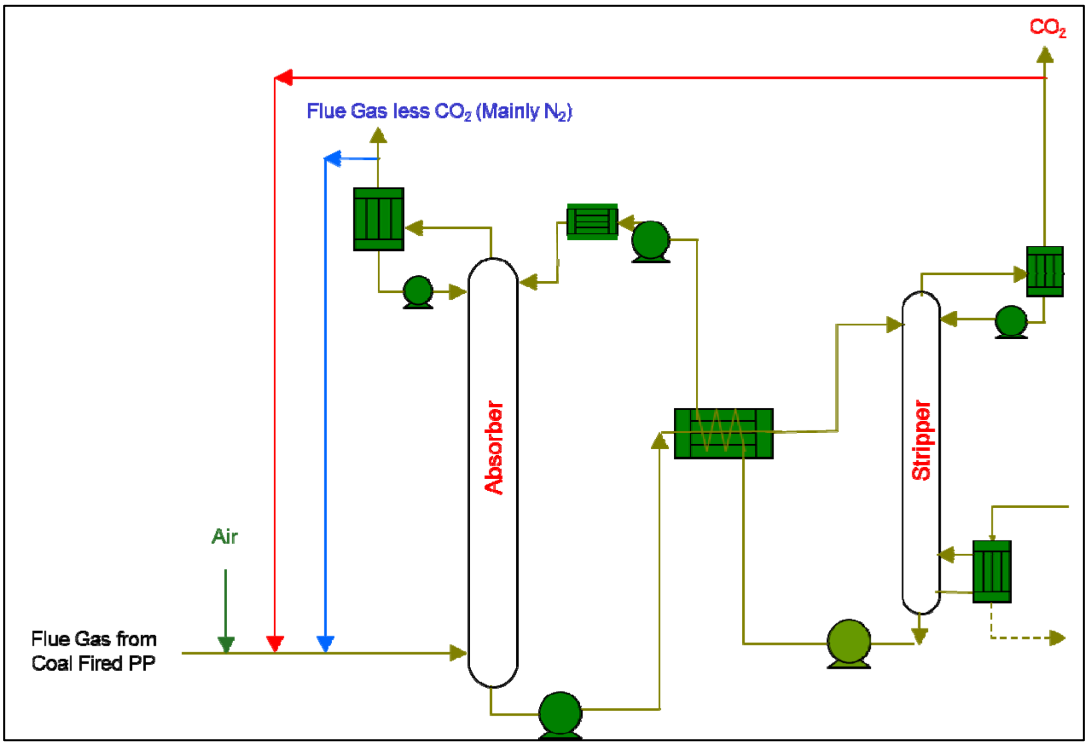

Fig.3.3.1 Schematic of Mikawa pilot plant modification

3.3.3 Test result for CO_2 containing gas from Iron & Steel plant

As shown above, the particular interest for this study would be the evaluation of capture performance when the technology is applied to lime kiln gas with CO_2 concentration of approximately 19 vol. %. The CO_2 enrichment line has been used to combine and simulate this flue gas.

Same has been conducted for evaluation of performance against hot blast stove gas with CO_2 concentration of approximately 29 vol. %.

Due to the complexity of the system, varying just only the CO_2 concentration of the inlet gas require intricate control several key equipments, such as solvent circulation pumps, the stem inlet valve, and the heat exchanger for cooling the lean solvent. Throughout the experiments, the essential parameters for designing a CO_2 capture plant were understood.

One of the most important data that cannot be acquired without experiment is the energy required for capturing CO_2. This is usually expressed in terms of GJ/t- CO_2 and is shown below. As shown, the energy requirement is lower with higher CO_2 concentration in the inlet gas. With the value of the energy requirement, the amount of steam needed for recovering CO_2 can be calculated. The experiment was carried out in 2013 by Toshiba.

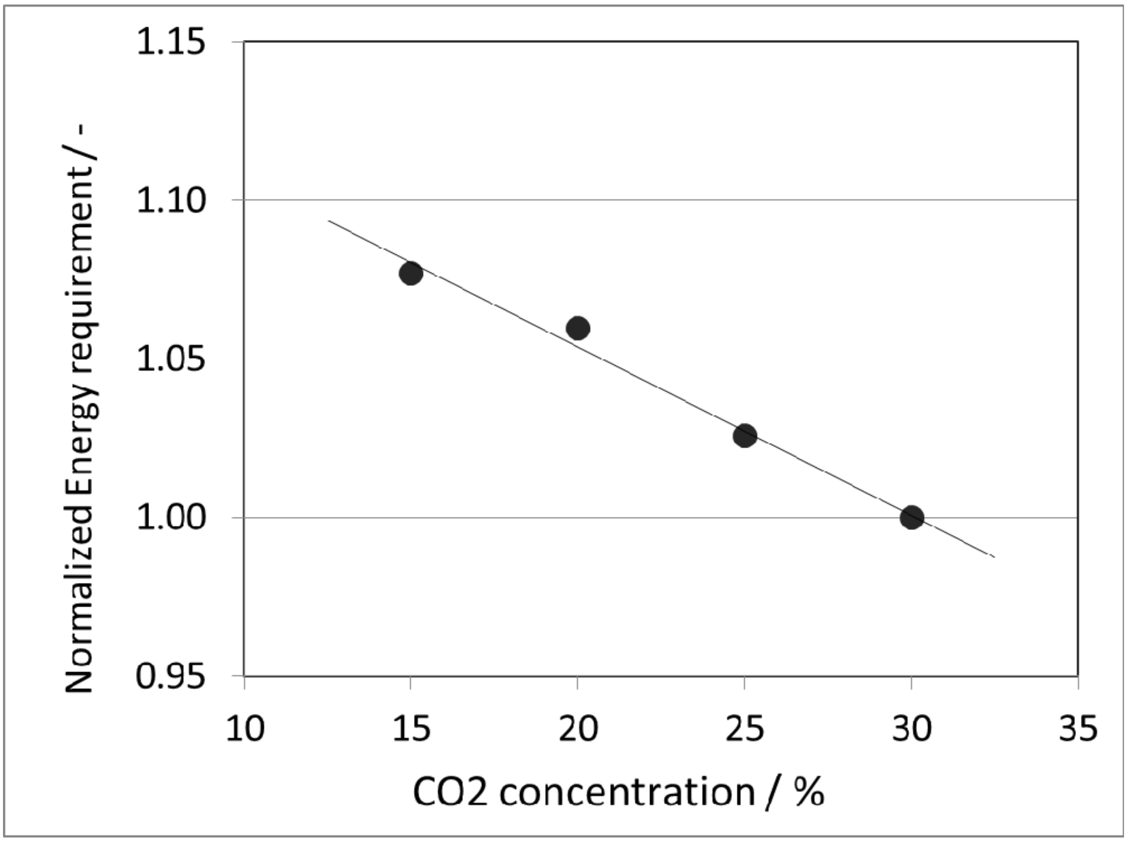

Fig.3.3.2 CO_2 concentration vs. Normalized energy requirement

3.4 CO_2 capture plant and compression design conditions

3.4.1 CO_2 Capture condition

CO_2 recovery rate and capture ratio are shown in Table 3.4.1

Table 3.4.1 CO_2 recovery rate and capture ratio

	Unit	Case1	Case2
CO_2 recovery rate	t/d	300	300
CO_2 capture ratio	%	90	90

3.4.2 Flue gas inlet condition (Heat source)

Inlet conditions of flue gas as heat source in the CO_2 capture plant are shown in Table 3.4.2.

Table 3.4.2 Flue gas condition as heat source

(CO_2 capture plant inlet; Point **A** in Fig.3.2.1 and Fig.3.2.2)

	Unit	Flue gas as heat source	
		Case1	Case2
Fluid source		Hot blast stove	Hot blast stove
Flow rate	m^3N/h	214,950	204,614
Temperature	deg C	258.4	258.4
Pressure	kPaA	100.9	100.9
Composition			
CO_2	vol.%	28.52	28.52
O_2	vol.%	2.51	2.51
N_2	vol.%	65.15	65.15
H_2O	vol.%	3.83	3.83

3.4.3 Flue gas outlet condition (Heat source)

Outlet conditions of flue gas as heat source in the CO_2 capture plant are shown in Table 3.4.3.

Table 3.4.3 Flue gas condition as heat source

(CO_2 capture plant outlet; Point **B** in Fig.3.2.1 and Fig.3.2.2)

	Unit	Flue gas as heat source	
		Case1	Case2
Fluid source		Hot blast stove	Hot blast stove
Flow rate	m^3N/h	214,950	204,614
Temperature	deg C	150.0	150.0
Pressure	kPaA	100.5	100.5
Composition			
CO_2	vol.%	28.52	28.52
O_2	vol.%	2.51	2.51
N_2	vol.%	65.15	65.15
H_2O	vol.%	3.83	3.83

3.4.4 Flue gas inlet condition (CO_2 source)

Inlet conditions of flue gas as CO_2 source in the CO_2 capture plant are shown in Table 3.4.4.

Table 3.4.4 Flue gas condition as CO_2 source

(CO_2 capture plant inlet; Point **C** in Fig.3.2.1 and Fig.3.2.2)

	Unit	Flue gas as CO_2 source	
		Case1	Case2
Fluid source		Lime kiln	Hot blast stove
Flow rate	m^3N/h	36,835	25,663
Temperature	deg C	110.0	155.7
Pressure	kPaA	102.3	102.2
Composition			
CO_2	vol.%	19.29	28.52
O_2	vol.%	12.87	2.51
N_2	vol.%	66.85	65.15
H_2O	vol.%	1.00	3.83

3.4.5 Flue gas outlet condition (CO_2 source)

Outlet conditions of flue gas as CO_2 source in the CO_2 capture plant are shown in Table 3.4.5.

Table 3.4.5 Flue gas condition as CO_2 source

(CO_2 capture plant outlet; Point **D** in Fig.3.2.1 and Fig.3.2.2)

	Unit	Flue gas as CO_2 source	
		Case1	Case2
Fluid source		Lime kiln	Hot blast stove
Flow rate	m^3N/h	30,286	19,114
Temperature	deg C	35.0	35.0
Pressure	kPaA	102.3	102.6
Composition			
CO_2	vol.%	2.44	4.98
O_2	vol.%	15.65	3.37
N_2	vol.%	81.30	87.46
H_2O	vol.%	0.61	4.19

3.4.6 CO_2 regeneration energy

Inlet conditions of steam required for the CO_2 capture plant are shown in Table 3.4.6. The conditions were determined by the latest result based on the Mikawa pilot plant test, which is indicated in clause 3.3. The steam is made by steam generator, which was planned in this study.

Table 3.4.6 Required steam rate at CO_2 capture plant

(CO_2 capture plant inlet; Point **E** in Fig.3.2.1 and Fig.3.2.2)

		Case1	Case2
Steam rate	GJ/h	31.00	29.26

3.4.7 CO_2 compression condition

Inlet and outlet conditions at CO_2 compression station are shown in Table 3.4.7 and Table 3.4.8. CO_2 compression conditions were determined in accordance with the CO_2 pipeline transport planned for this study.

Table 3.4.7 CO_2 compression condition

(CO_2 compression station inlet; Point **F** in Fig.3.2.1 and Fig.3.2.2)

		Case1	Case2
Flow rate	m^3N/h	6,480	6,480
Temperature	deg C	35.0	35.0
Pressure	kPaA	203.2	203.2
Composition			
CO_2	vol.%	97.19	97.20
O_2	vol.%	0.008	0.001
N_2	vol.%	0.04	0.03
H_2O	vol.%	2.77	2.77

Table 3.4.8 CO_2 compression condition

(CO_2 compression station outlet; Point **G** in Fig.3.2.1 and Fig.3.2.2)

		Case1	Case2
Flow rate	m^3N/h	6,307	6,307
Temperature	deg C	40.0	40.0
Pressure	kPaA	10,000	10,000
Composition			
CO_2	vol.%	99.85	99.87
O_2	vol.%	0.008	0.001
N_2	vol.%	0.04	0.03
H_2O	vol.%	0.10	0.10

4. CO_2 capture system description

4.1 Case 1: Lime kiln case

4.1.1 Design of the CO_2 capture system

Attachment-4.1.1 and Fig.4.1.1 show the process flow diagram (PFD) and schematic of the CO_2 capture system for Case1, which includes the following systems;

(1) Gas pretreatment system;

(2) CO_2 absorption system (gas source: lime kiln gas);

(3) CO_2 regeneration system;

(4) Steam generation system (heat source: hot blast stove flue gas);

(5) CO_2 compression and dehydration system;

(6) CO_2 transport system;

(7) Water supply system (Cooling water, Demineralized water, Industrial water);

(8) Wastewater sump system;

In addition, major equipment lists for CO_2 capture plant are shown in Attachment-4.1.2.

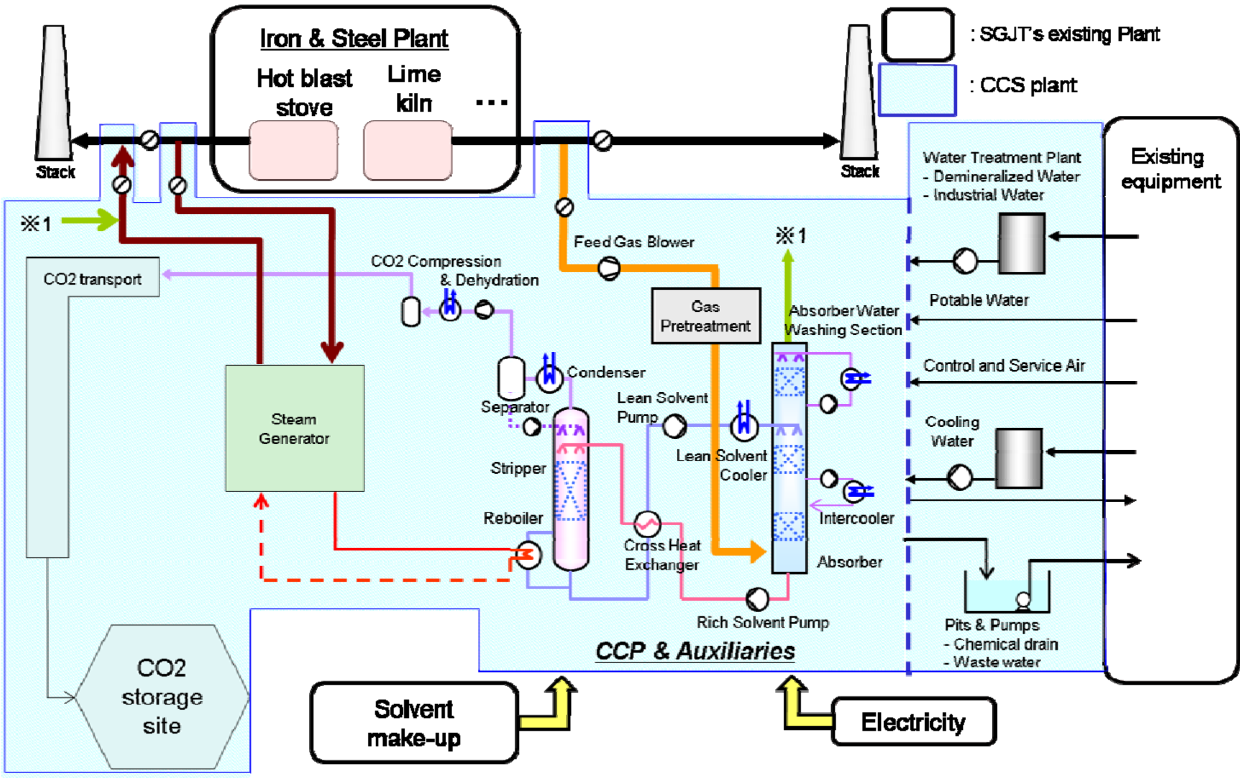

Fig.4.1.1 Schematic of CO_2 capture system (Case1)

(1) Gas pretreatment system

Based on trapping and analyzing the flue gas from #4 lime kiln in this study, trace constituents except for the components described in clause 3.4 are shown in Table 4.1.1.

Table 4.1.1 Trace constituents from #4 lime kiln (Case1)

Component	Concentration
SOx	1.5 ppm
NOx	37.6 ppm
Dust	< 20 mg/ m^3N

The trace constituents are so infinitesimally small, that they do not affect CO_2 capture plant operation and the solvent performance. Therefore, gas pretreatment system only has to cool the flue gas entering into the absorber. In other words, gas pretreatment system acts equivalent to a heat exchanger. After lime kiln gas passed through the bag-type dust filter, part of the flue gas is imported into the gas pretreatment system through feed gas blower. After the flue gas passed through the gas pretreatment system, it will be cooled down to 35 deg C before it enters the absorber. The flue gas is cooled by the cooling medium of the cooling water provided by the existing facility.

(2) CO_2 absorption system (gas source: lime kiln gas)

The lime kiln gas cooled down to 35 deg C at the gas pretreatment system will be imported to the absorber. In the absorber tower, the flue gas moves from bottom to top, and the CO_2 lean solvent from the stripper is fed from top and travels downwards through the packing to make the solvent fully contact with the flue gas.

Due to an exothermic reaction, the temperature in the absorber will rise, and consequently, the reaction rate will decrease. Therefore, in order to ensure a smooth and rapid absorption process, intercoolers will be installed in middle part of the absorber for evenly low solvent temperature in the absorber.

In the top section of the absorber, in order to minimize the amount of the entrainment carried in the flue gas, circulated water will clean the flue gas to wash away the entrainment and amine containing component in the flue gas.

CO_2 removed flue gas at the absorber will be emitted by the original chimney of the hot blast stove, which is located near the CO_2 capture plant.

(3) CO_2 regeneration system

After passing through the solvent cross heat exchanger, the rich solvent from bottom of the absorber will enter into top of the stripper, flowing downward from top of the stripper through the packing. In stripper, regeneration of CO_2 is typically realized through heating by reboiler. Steam of the reboiler is fed from the steam generator, and heat of the steam generator is from flue gas of the hot blast stove. The flue gas imported from the hot blast stove will be exported back to the hot blast stove chimney through exhaust gas blower after passing through the steam generator.

(4) Steam generation system (heat source: hot blast stove flue gas)

In order to achieve effective use of extra heat in the existing iron and steel plant, steam generator will be planned to make steam for CO_2 capture system.

Part of the flue gas in hot blast stove will be imported into the steam generator as heat source. After it is cooled through the steam generator, it will be exported back to the hot blast stove chimney through an exhaust gas blower to be emitted into the atmosphere.

On the other hand, demineralized water in the steam generator will be heated to steam for the use of CO_2 capture system, and supplied to the reboiler. Steam condensed back to water in reboiler as steam drain, will be used again to generate steam continuously. .

(5) CO_2 compression and dehydration system

The gas flows out from upper part of the stripper and enters into the four-section CO_2 compressor after through stripper condenser and separator, in which inlet temperature is 35 deg C, pressure is 203.2 kPaA.

Due to the inlet stream being fully saturated with water, the water content of the outlet compressor stream will be above the 0.10% requirement. To mitigate risk of corrosion in the pipeline, dehydration will be necessary. Although there are multiple methods that can be used for dehydration, this study is based on using an adsorbent to dehydrate the gas which is a proven method and will be capable of achieving the 0.10% water content.

In order to achieve water content of 0.10% or below for the compressor station outlet stream, it will be optimal to take the CO_2 stream between the 3rd and 4th stages due to the water holding capacity of CO_2 being at a low point for this particular compression process.

The wet gas from the compressor will be taken downstream of the 3rd stage discharge cooler and will be sent to an adsorption tower. The dry gas from the tower will then be directed back to the compressor at the 4th stage suction for final compression.

(6) CO_2 transport system

See clause 5.2 CO_2 Transport.

(7) Water supply system (Cooling water, Demineralized water, Industrial water)

Cooling water for CO_2 capture plant will be supplied from existing iron and steel plant through a cooling trough in which the water will be stored temporarily. The cooling water will directly return to the existing plant after used in CO_2 capture plant's heat exchangers.

Demineralized water and industrial water will also be supplied from existing iron and steel plant through the tanks respectively in which the water will be stored temporarily.

(8) Wastewater sump system

Existing waste water treatment facilities are to be utilized.

4.1.2 Heat and Mass Balance of the Plant

See Attachment-4.1.3.

4.1.3 Plot Plan and General Arrangement of the Plant

(1) CO_2 capture plant location candidate

According to the plan to use exhaust heat of the hot blast stove flue gas for CO_2 capture plant operation, it is necessary for CO_2 capture plant location to select it near the hot blast stove so that heat loss caused by the heat radiation will be reduced. Therefore, we chose the following three sites proposed by SGJT for site survey. (See Fig.4.1.2)
In this FS, we studied candidate 2 where it was confirmed that there were no existing underground structures which would come in the way of constructing the CO_2 capture plant.

There are underground structures in candidate 1, mainly including cables and industrial water pipelines. Candidate 3 is a reserved zone for technological transformation, which is used for other purposes. So far we have confirmed candidate 2 as a CO_2 capture plant construction site for this project.

(2) CO_2 capture plant scale

See Attachment-4.1.4, Attachment-4.1.5, and Attachment-4.1.6 of General arrangement and side view, which was designed for Case1. CO_2 capture plant scale is shown in Table 4.1.2.

Table 4.1.2　CO_2 capture plant scale (Case1)

Plant	Scale
CO_2 capture plant	53.1m(L)×40.5m(W) ×51.7m(H: absorber)

(3) Plot plan of CO_2 capture plant in Caofeidian iron and steel plant

See Attachment-4.1.7, drawing plot plan of CO_2 capture plant in Caofeidian iron and steel plant. The duct length of lime kiln gas as CO_2 source is approximately 2,240m, and hot blast stove flue gas as heat source is approximately 680m.

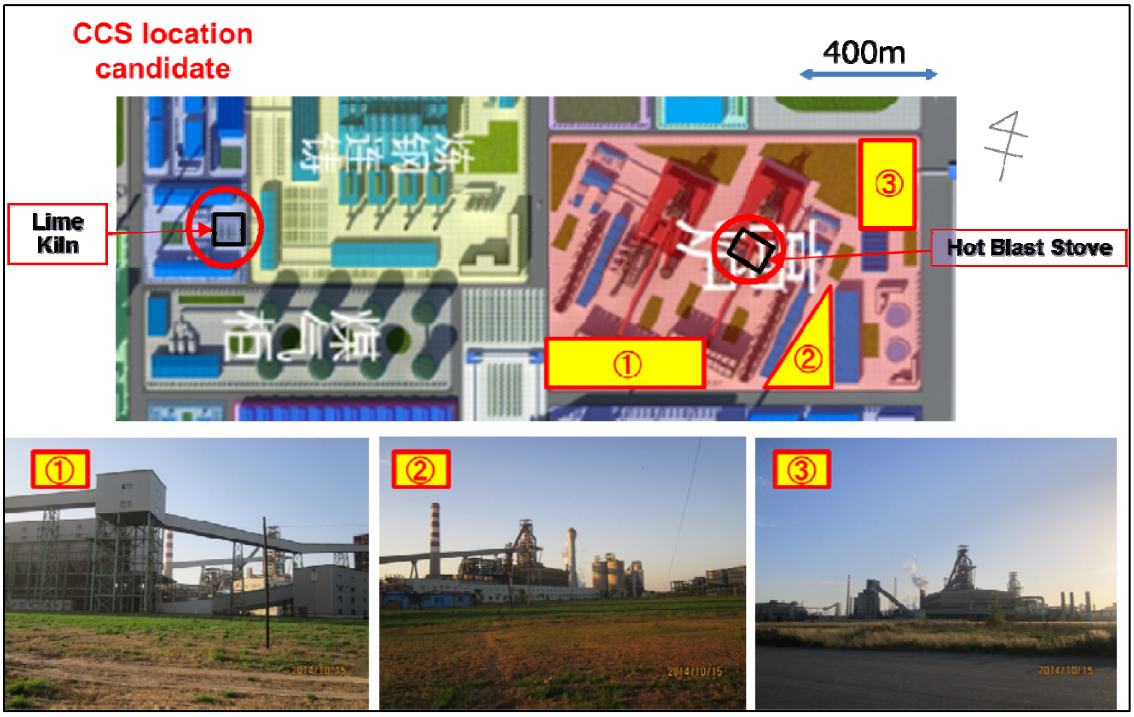

Fig.4.1.2 CCS location candidate

(4) CO_2 capture plant 3D view

3D view of CO_2 capture plant of 300t/d in Caofeidian iron and steel plant.is shown in Fig. 4.1.3, Fig.4.1.4 and Fig.4.1.5.

In Case1, the flue gas as CO_2 source will be imported from the lime kiln, and CO_2 removed flue gas at the absorber will be emitted by the original chimney of the hot blast stove, which is located near the CO_2 capture plant.

On the other hand, Part of the flue gas in hot blast stove will be imported into the steam generator as heat source. After it is cooled through the steam generator, it will be exported back to the hot blast stove chimney through an exhaust gas blower to be emitted into the atmosphere.

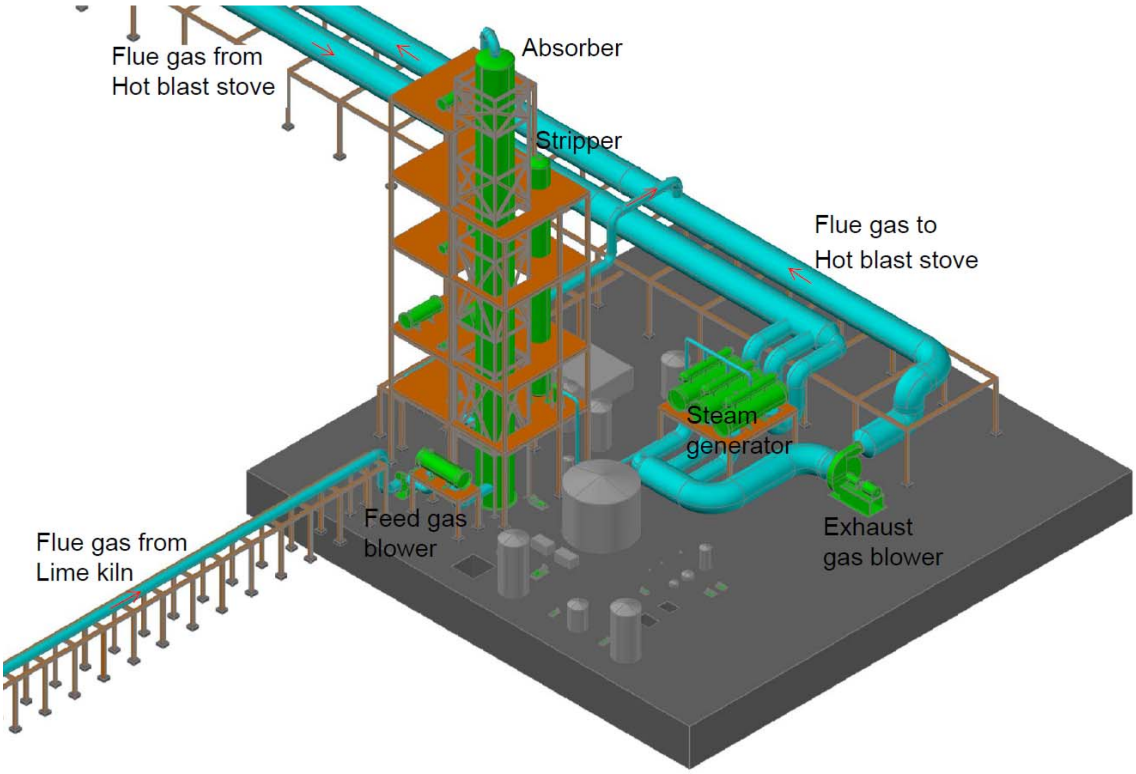

Fig. 4.1.3 CO_2 capture plant

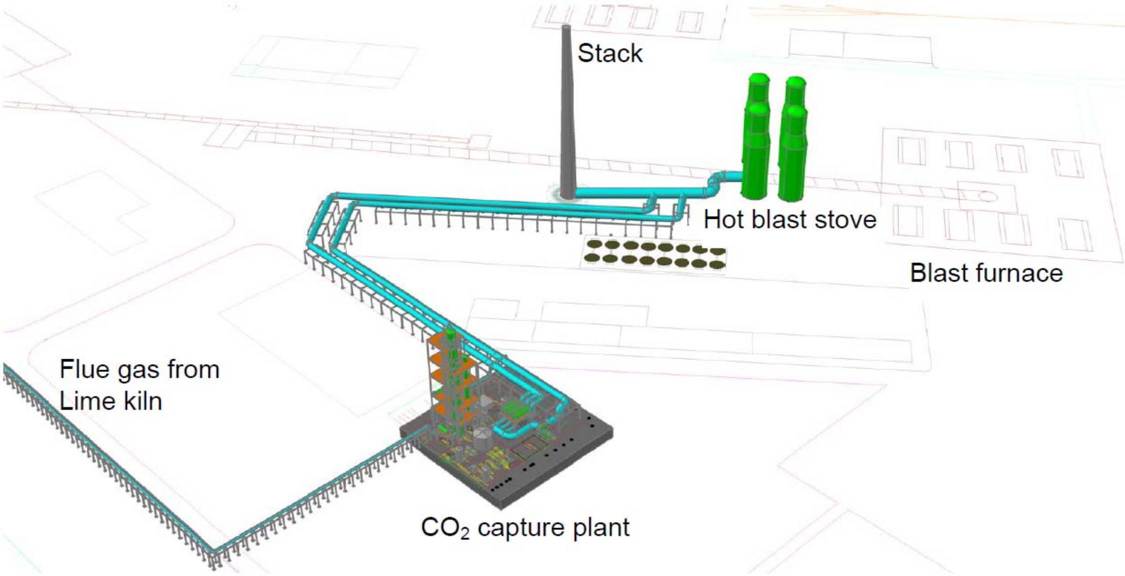

Fig. 4.1.4 CO_2 capture plant in Caofeidian iron and steel plant (View from East)

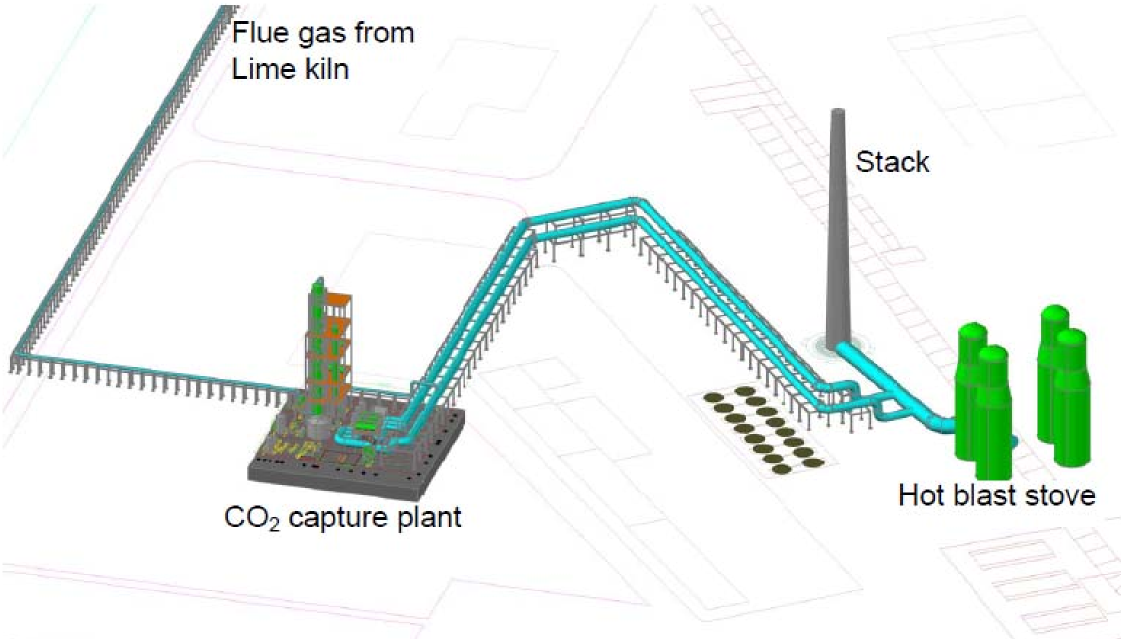

Fig. 4.1.5 CO_2 capture plant in Caofeidian iron and steel plant (view from North)

4.2 Case 2: Hot Blast Stove case

4.2.1 Design of the CO_2 capture system

Attachment-4.2.1 and Fig.4.2.1 show the process flow diagram (PFD) and schematic of the CO_2 capture system for Case2, which includes the following systems;

(1) Gas pretreatment system;
(2) CO_2 absorption system (gas source: hot blast stove flue gas);
(3) CO_2 regeneration system;
(4) Steam generation system (heat source: hot blast stove flue gas);
(5) CO_2 compression and dehydration system;
(6) CO_2 transport system;
(7) Water supply system (Cooling water, Demineralized water, Industrial water);
(8) Wastewater sump system;

In addition, major equipment specification lists for CO_2 capture plant are shown in Attachment-4.2.2.

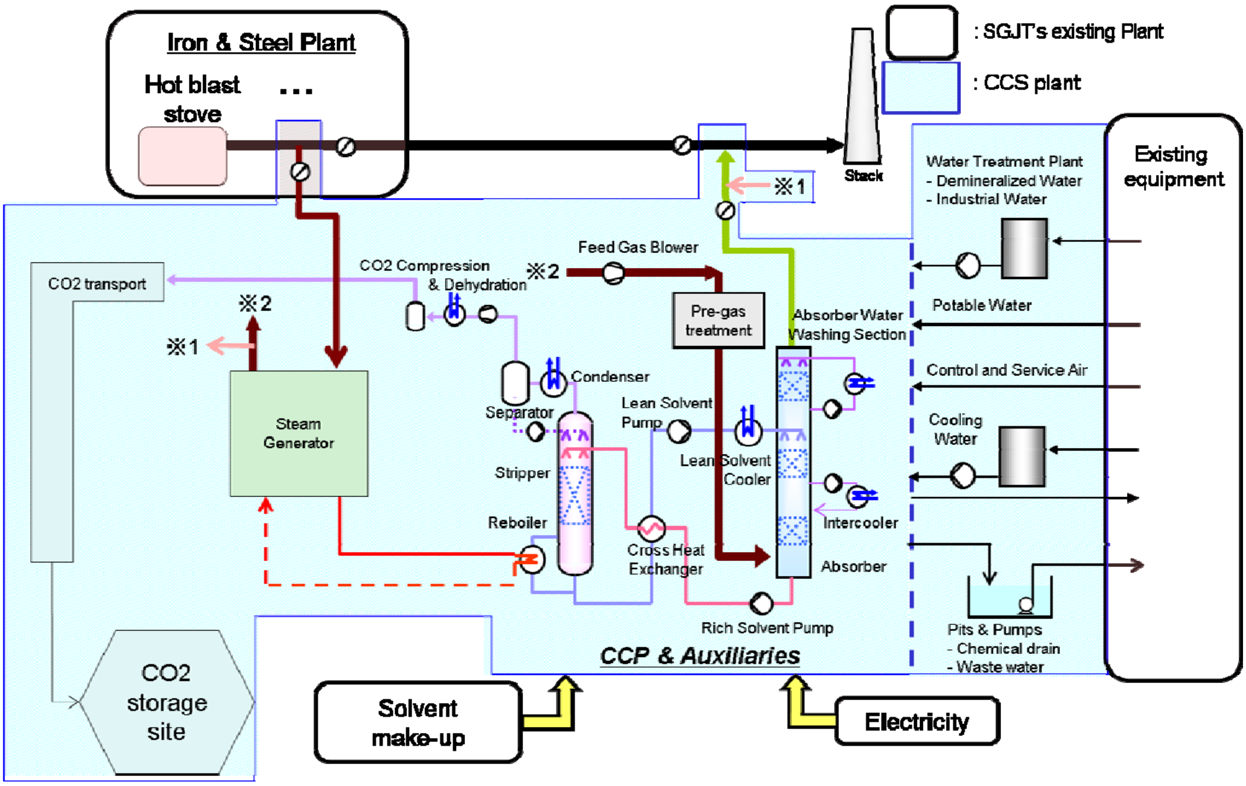

Fig.4.2.1 Schematic of CO_2 capture system (Case2)

(1) Gas pretreatment system

Based on trapping and analyzing flue gas from #3&4 hot blast stove in this study, trace constituents except for the components described in clause 3.4 are shown in Table 4.2.1.

Table 4.2.1 Trace constituents from #3&4 hot blast stove (Case2)

Component	Concentration
SOx	6.0 ppm
NOx	12.0 ppm
Dust	< 20 mg/ m^3N

The trace constituents are so small that they do not affect CO_2 capture plant operation and the solvent performance. Therefore, gas pretreatment system only has to cool the flue gas entering into the absorber. In other words, gas pretreatment system is equivalent of a heat exchanger. After #3&4 hot blast stove flue gas passed through the steam generator, part of the flue gas is imported into the gas pretreatment system through feed gas blower. After the flue gas passed through the gas pretreatment system, it will be cooled down to 35 deg C before it enters the absorber. The flue gas is cooled by the cooling medium of the cooling water provided by the existing facility.

(2) CO_2 absorption system (gas source: hot blast stove flue gas)

The hot blast stove flue gas cooled down to 35 deg C at the gas pretreatment system will be imported to the absorber. In the absorber tower, the flue gas moves from bottom to top, and the CO_2 lean solvent from the stripper is fed from top downwards through the packing to make the solvent fully contact with the flue gas.

Due to an exothermic reaction, the temperature in the absorber will rise, and as a result, reaction rate will decrease. Therefore, in order to ensure a smooth and rapid absorption process, intercoolers will be installed in middle part of the absorber for evenly low solvent temperature in the absorber.

In the top section of the absorber, in order to minimize the amount of the entrainment carried in the flue gas, circulated water will clean the flue gas to wash away the entrainment and amine containing component in the flue gas.

CO_2 removed flue gas at the absorber will be emitted by the original chimney of the hot blast stove located near the CO_2 capture plant.

(3) CO_2 regeneration system

After passing through the solvent cross heat exchanger, the rich solvent from bottom of the absorber will enter into top of the stripper, flowing downward from top of the stripper through the packing. In stripper, regeneration of CO_2 is typically realized through heating by reboiler. Steam of the reboiler is fed from the steam generator, and heat of the steam generator is from flue gas of the hot blast stove. The flue gas imported from the hot blast stove will be exported back to the hot blast stove chimney through exhaust gas blower after passing through the steam generator.

(4) Steam generation system (heat source: hot blast stove flue gas)

In order to achieve effective use of extra heat in the existing iron and steel plant, steam generator will be planned to make steam for CO_2 capture system.

Part of the flue gas in hot blast stove will be imported into the steam generator as heat source. After it is cooled through the steam generator, it will be exported back to the hot blast stove chimney through an exhaust gas blower to be emitted into the atmosphere.

On the other hand, demineralized water in the steam generator will be heated to steam for the use of CO_2 capture system, and supplied to the reboiler. Steam condensed back to water in reboiler as steam drain, will be used again to generate steam.

(5) CO_2 compression and dehydration system

The gas flows out from upper part of the stripper and enters into the four-section CO_2 compressor after through stripper condenser and separator, in which inlet temperature is 35 deg C, pressure is 203.2 kPaA.

Due to the inlet stream being fully saturated with water, the water content of the outlet compressor stream will be above the 0.10% requirement. To mitigate risk of corrosion in the pipeline, dehydration will be necessary. Although there are multiple methods that can be used for dehydration, this study is based on using an adsorbent to dehydrate the gas which is a proven method and will be capable of achieving the 0.10% water content.

In order to achieve water content of 0.10% or below for the compressor station outlet stream, it will be optimal to take the CO_2 stream between the 3rd and 4th stages due to the water holding capacity of CO_2 being at a low point for this particular compression process. The wet gas from the compressor will be taken downstream of the 3rd stage discharge cooler and will be sent to an adsorption tower. The dry gas from the tower will then be directed back to the compressor at the 4th stage suction for final compression.

(6) CO_2 transport system

See clause 5.2 CO_2 Transport.

(7) Water supply system (Cooling water, Demineralized water, Industrial water)

Cooling water for CO_2 capture plant will be supplied from existing iron and steel plant through a cooling trough in which the water will be stored temporarily. The cooling water will directly return to the existing plant after used in CO_2 capture plant's heat exchangers.

Demineralized water and industrial water will also be supplied from existing iron and steel plant through the tanks respectively in which the water will be stored temporarily.

(8) Wastewater sump system

Existing waste water treatment facilities are to be utilized.

4.2.2 Heat and Mass Balance of the Plant

See Attachment-4.2.3.

4.2.3 Plot Plan and General Arrangement of the Plant

(1) CO_2 capture plant location candidate

According to the plan to use exhaust heat of the hot blast stove flue gas for CO_2 capture plant operation, it is necessary for CO_2 capture plant location to select it near the hot blast stove so that heat loss caused by the heat radiation will be reduced. Therefore, we chose the following three sites proposed by SGJT for site survey. (See Fig.4.1.2)

In this FS, we studied candidate 2 where it was confirmed that there were no existing underground structures which would come in the way of constructing the CO_2 capture plant.

(2) CO_2 capture plant scale

See Attachment-4.2.4, Attachment-4.2.5, and Attachment-4.2.6 of General arrangement and side view, which was designed for Case2. CO_2 capture plant scale is shown in Table 4.2.2.

Table 4.2.2 CO_2 capture plant scale (Case1)

Plant	Scale
CO_2 capture plant	53.1m(L)×40.5m(W) ×51.5m(H: absorber)

(3) Plot plan of CO_2 capture plant in Caofeidian iron and steel plant

See Attachment-4.2.7, drawing plot plan of CO_2 capture plant in Caofeidian iron and steel plant. The duct length of hot blast stove flue gas as CO_2 source is approximately 60m, and hot blast stove flue gas as heat source is approximately 680m.

(4) CO_2 capture plant 3D view

3D view of CO_2 capture plant of 300t/d in Caofeidian iron and steel plant.is shown in Fig. 4.2.2, Fig.4.2.3 and Fig.4.2.4.

In Case2, the flue gas as CO_2 source after used in the steam generator will be imported from the hot blast stove, and CO_2 removed flue gas at the absorber will be emitted by the original chimney of the hot blast stove located near the CO_2 capture plant.

On the other hand, Part of the flue gas in hot blast stove will be imported into the steam generator as heat source. After it is cooled through the steam generator, it will be exported back to the hot blast stove chimney through an exhaust gas blower to be emitted into the atmosphere.

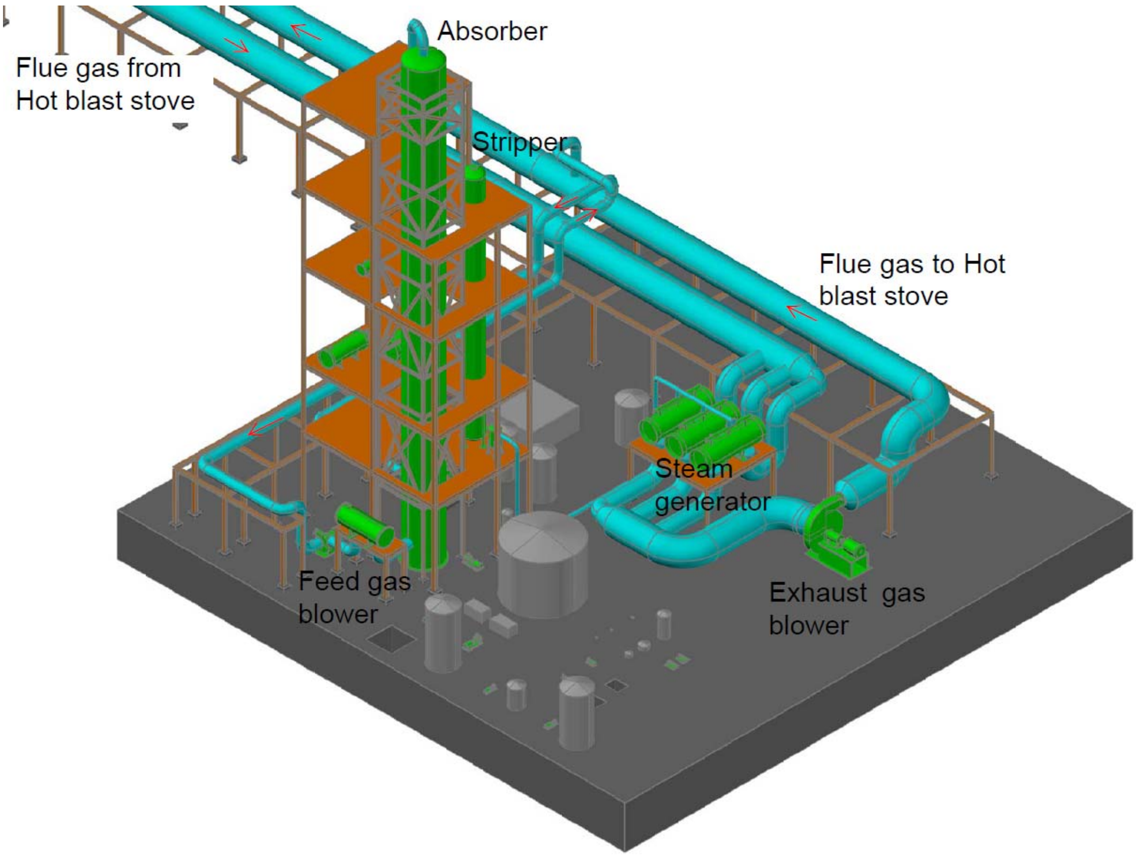

Fig. 4.2.2 CO_2 capture plant

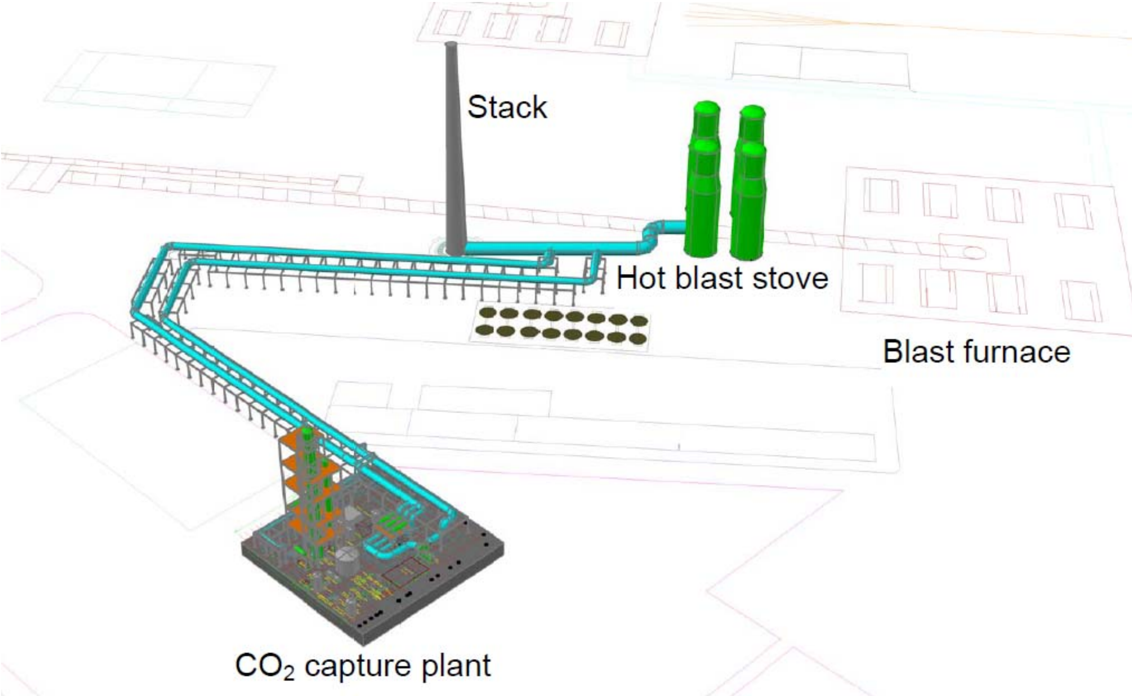

Fig. 4.2.3 CO_2 capture plant in Caofeidian iron and steel plant (View from East)

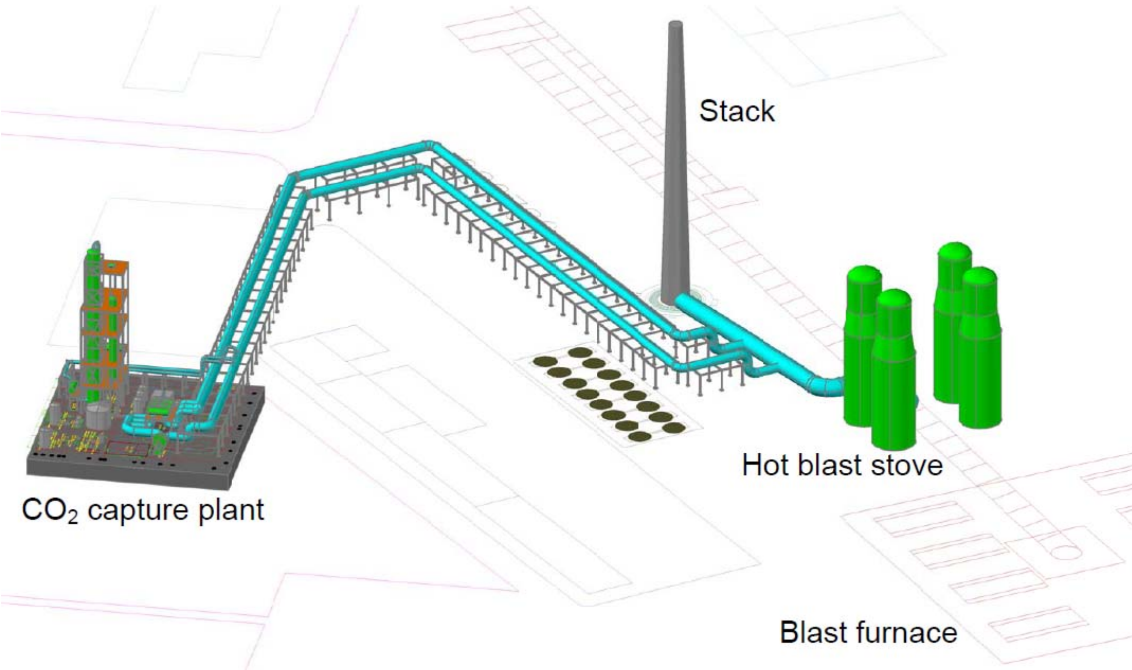

Fig. 4.2.4 CO_2 capture plant in Caofeidian iron and steel plant (view from North)

5. CO_2 Transport, Usage (Storage) Description

5.1 CO_2 Usage (Storage) potential

In view of characteristics of China, Toshiba outsourced survey work to a research company in China. The data utilized in this clause, is based on the results surveyed by Crediteyes Co., Ltd., Toshiba normalized some of the data when in necessary and drew a diagram of the data.

5.1.1 CO_2 Usage current situation

The overall market utilization level of CO_2 is low. But seen from long-term, the prospect for development is promising due to extensive demand of CO_2.

In the early 1980s, China's synthesis ammonia plants and alcohol plants began to recycle discharged CO_2, basically self-production and self-use or producing according to sales. Now, as is an important industrial gas, CO_2 is extensively used in food industry, chemical industry, machinery industry, agriculture, commerce, transport, oil exploration, national defense, fire protection and other departments.

The statistic usage amount of carbon dioxide in 2013 is 3 million tons. In addition, some companies recycle and reuse carbon dioxide by their own equipment, which suggests that the actual usage amount of carbon dioxide is larger than statistic usage amount.

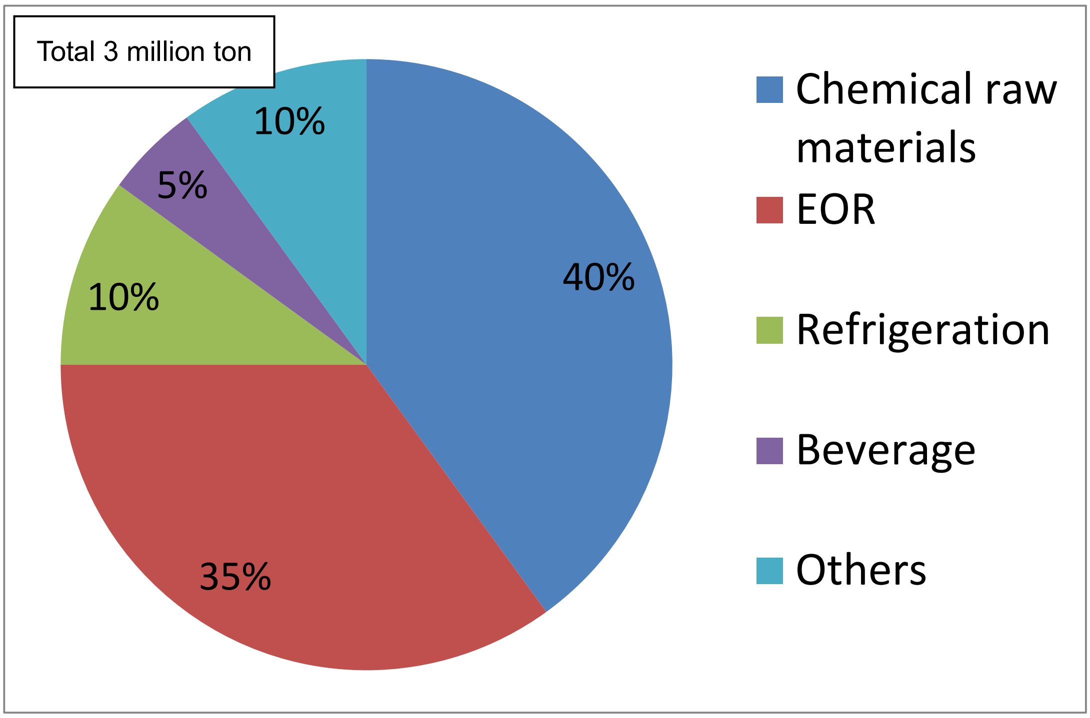

Fig. 5.1.1 China's CO_2 Utilization Structure Chart In 2013

Fig. 5.1.1 is about the consumption structure of China's CO_2. According to this figure, we can see that chemical industry and petroleum industry are the main application area of China's CO_2 with the proportion of 75(40+35)%. The refrigeration industry, the beverage industry and other industries are at a low proportion. With the development of the application area of CO_2, it is estimated that the demand will be increased.

The CO_2 displacement of reservoir oil technology has a long history to be used in China's oil industry. With the approaching of the "Carbon Trading" in recent years, popularization and accelerating of the technology, there have been several domestic oilfield CO_2-EOR demonstration projects.

5.1.2 Specific Example of CO_2 Usage (Storage)

Since 2013 China's CCS development process is accelerating, which is driven by policy promoted by NDRC.

Table 5.1.1 summarizes the active and ongoing CCUS/CCS projects. Seen from the table, steel industry has not yet had CCUS large projects. Domestic carbon recycle resources are mainly used for EOR or sealing now, and some are used for food and beverage industries.

Table 5.1.1 China's carbon recycling items and utilization situation

	Project Name	Project Proponents	Location	Scale	Source / Usage	Status	Citation
1	PetroChina Jilin Oil Field EOR Project (Phase 1)	Capture, Transport and Storage: Jilin Oil Field, China National Petroleum Company (CNPC)	Jilin Province, China	Phase 1 150,000 Phase 2 800,000	NG processing / EOR	Phase 1 operation in 2009	GCCSI HP
2	Huaneng GreenGen IGCC Project (Phase 2)	Capture: China Huaneng Gr., et. al Transport and Storage: Not specified	Lingang Industrial Park, Binhai New Area, Tianjin, China	Phase 1 0 Phase 2 60,000 PHase 3 2,000,000	IGCC / Phase 1 constr. Phase 2 EOR Phase 3 EOR	Phase 1 completed in 2012 Phase 2 started constr. in 2014	GCCSI HP
3	Sinopec Qilu Petrochemical CCS	Capture, Transport and Storage: China Petrochemical Corporation	Shandong Province, China	350,000(2016) 500,000(2018)	Coal gasification / EOR	FEED completed	GCCSI HP
4	Shenhua Ordos CTL Project (Phase 1)	Capture, Transport and Storage: Shenhua Group	Inner Mongolia, China	Phase 1 total 17,000 Phase 2 1,000,000	Coal to Liquids / geological storage	Phase 1 started in 2011	GCCSI HP
5	Yanchang Integrated Demonstration Project	Capture, Transport and Storage: Shaanxi Yanchang Petroleum Group	Shaanxi Province, China	50,000(2012) 460,000(2016)	Coal gasification / EOR	iniection started in 2012	GCCSI HP
6	Huaneng Gaobeidian Power Plant Pilot Project	China Huaneng Group	Huaneng Gaobeidian	3,000	Power Plant / food and beverage	operation in 2008	GCCSI HP
7	Huazhong Univ. of Sci. and Tech. Oxyfuel PJ	The Huazhong Univ. of Sci. and Tech. (HUST) et al.	Yingcheng, Hubei Province, China	3MWth : 7,000 35MWth: 100,000	oxy-fuel / storage utilization	3MW completed in 2011 35MW under construction	GCCSI HP
8	Shanghai Shidongkou 2nd Power Plant Demonstration PJ	China Huaneng Group	Shanghai Shidongkou, Shanghai, China	100,000	Power Plant / beverage	operation in 2009	GCCSI HP
9	Sinopec Shengli Oilfield Pilot Project	Sinopec Shengli Oilfield Company	Shandong Province, China	30,000	Power Plant / EOR	operation in 2010	GCCSI HP
10	Sinopec Zhongyuan Pilot Project	Sinopec Zhongyuan Oilfield Company	Zhongyuan Oil Field, Henan Province, China	20,000 (100,000 FS completed)	Fluidized Catalytic Cracker flue gas / EOR	operation in 2006	GCCSI HP
11	Jingbian Project	Shaanxi Yanchang Petroleum Co.	Jingbian Field Qiaojiawa, Shanxi Province, China	40,000	coal chemical / EOR	operation in 2013	MIT HP
12	Inner Mongolia CO_2 Geology Storage Project	unknown	Inner Mongolia, Jungar Banner	1,000,000	Coal chemical industry / sealing	started in 2011	Crediteye
13	Zhongke Jinlong CO_2 chemical utilization item	Chinese Academy of Sciences	Jiangsu, Taixing	10,000	Alcohol plant / plastics	operation in 2007	Crediteye
14	CNOOC CO2 degradable p	Chinese Academy of Sciences	Hainan, Dongfang City	2,100	Natural gas separation / plastics	operation in 2009	Crediteye
15	Guodian Group CO_2 capture and utilization demonstration project	China Guodian Corporation	Tianjin, Tanggu District	20,000	combustion flue gas / food	operation in 2011	Crediteye
16	CPI Chongqing Shuanghuai CPI Carbon Capture Demonstration	CPI Yuanda	Chongqing, Hechuan	10,000	combustion flue gas / beverage	operation in 2010	Crediteye
17	Enn Microalgae Carbon Sequestration Biological Energy Source	Hebei ENN Group	Inner Mongolia, Dalad Banner	20,000	Coal chemical industry / microalgae	Construction in 2011	Crediteye

5.2 CO_2 transport

CO_2 that was captured from the process in the iron and steel plant can be transported through tanker or pipeline to the field for EOR, and this feasibility study focuses on CO_2 pipeline transportation solutions.

5.2.1 CO_2 pipeline transport process

The distance from the starting point of CO_2 transport system to Liuzan North Region in Jidong Oilfield, where is shown in clause 5.3.2, is expected to be 40 km. The altitude of the CO_2 pipleine starting point is -1m, and the end point is 4m, The landscape between these points are primarily flat with a height difference between the end and the start of only 5m.

5.2.2 CO_2 pipeline conditions

Design data of the CO_2 pipeline are shown below:

Table 5.2.1 CO_2 Pipeline Design data

Name		Unit	Parameter
Pipeline inlet	Temperature	deg C	40
	Pressure	MPa	10
	Flow rate	m^3/h	16.21
Pipeline outlet	Temperature	deg C	38
	Pressure	MPa	8.7
Pipe length		km	40

Super critical CO_2 is exported from CO_2 surge tank and transported directly by pipeline to the oilfield. The distance from CO_2 capture plant to EOR site is relatively short in this feasibility study. Therefore, it is not necessary to establish the CO_2-boost-up facilities on the pipeline because of low pressure drop. CO_2 pressure is kept above the super critical pressure at the endpoint of pipeline.

5.3 Usage (Storage) area around the Plant

5.3.1 Introduction of Jidong oilfield

Petro China Jidong Oilfield is a regional company directly subordinate to the China National Petroleum Corp. with main businesses of oil and gas exploration, development and sales. It is located in the northern coast of the Bohai Bay and headquartered in Tangshan City. Oilfield exploration and development covers two cities and seven counties, such as

Tangshan, Qinhuangdao, Tanghai, etc., and the total area is 6,300m^2, of which 3600 m^2 is land portion, and 2,700 m^2. is intertidal zone and very shallow sea. Seven oilfields have been found,in this area, such as Gaoshangpu, Liuzan, Yanggezhuang, etc. By the end of 2005, reserves amount to 176.62 million tons of the total proven oil.

5.3.2 Oil well overview in Liuzan North region

Liuzan North Region is an important oil-producing region of onshore portion in Jidong Oilfield. Currently, the well area stays in a water-cut period, and the recovery percent of reserves is relatively low and the remaining oil potential is large. However, ever since the blocks entered in the water-flooding stage, the water injection pressure has increased rapidly, especially those near root of the fault. The injection pressure for the majority of these wells is close to 30MPa. Due to such difficulty in water injection, failure in long-term effective supplement of the formation energy has put these wells with “three lows” production characteristics, namely low oil production, low water content and low working fluid level. To improve this situation, it is considered a must to actively change the development mode of the reservoir towards research and demonstration in the application of CO_2 flooding instead of water flooding.

After investigation, Jidong Oilfield has carried out CO_2 flooding test for four injection wells in Liuzan North Region, and they are LB1-16, LB1-28, LB1-19-20 and LB1-30 well respectively, of which, LB1-16 and LB1-28 are the first round injection wells, and LB1-19-20 and LB1-30 are new wells. The first round gas injection construction of two wells has been completed from November 2011 to December 2012, and the cumulative gas injection was 14,640 tons. Dynamic monitoring showed that reservoir energy at the gas injection phase recovered gradually, and the average working fluid level raised from 1990 m to 1500 m, and daily oil production in peak period increased about 25 tons compared with that before gas injection. At the end of gas injection, oil recovery at the test site increased 2.54%, and the first round gas injection construction obtained preliminary results.

Considering this situation as described above, site of this feasibility study EOR has been set to Liuzan North Region in Jidong Oilfield, and take LB1-30 well as the object of study to prepare EOR program. CO_2 pipeline path is as shown in the following Figure.

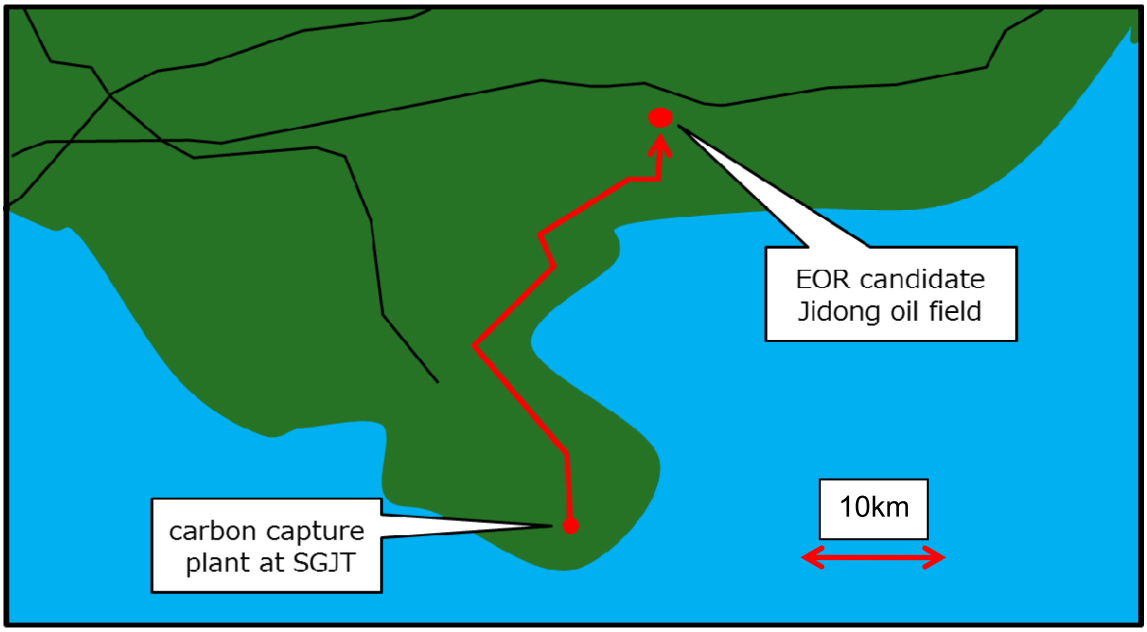

Fig. 5.2.1 CO_2 transportation path

5.3.3 EOR condition

It has been reported here that the use of CO_2 as medium for production enhancement can help improve oil recovery by 7% to 15%.

After 40km transportation of liquid CO_2, it will be transported to EOR injection point ,namely LB1-30 well of Liuzan North Region in Jidong Oilfield by Shougang Jingtang.

These reservoir are of high porosity, high permeability and strong heterogeneous type. The design wellhead injection pressure is 30MPa.

Process utilized here is CO_2 huff-puff process with the total injection volume (liquid CO_2) at 0.1Mtpa (300t/d), injection rate (liquid CO_2) at 389m^3/d. Huff-puff is divided into three cycles, and injection volume of each cycle is 4668m^3, 3112m^3 and 3112m^3 respectively. Soak time is about 15d.

Referring to experimental data of Jidong Oilfield [2], with huff-puff effect under this injection condition, oil recovery is expected to increase 1.8%, and enhanced production of oil per well is 916t, of which huff-puff effective stimulation period is about 237 days.

According to survey on Shougang, existing CO_2 used for oil recovery is costing 500 RMB /ton (or 80 USD/ton).

6. Project Evaluation

6.1 Assessment of Project Options and its Economics

6.1.1 Method of Economic Evaluation

As it is generally common amongst all carbon capture and storage projects around the world, present legal or regulatory framework itself do not force implementation of carbon capture technology to CO_2 emissions. Additionally, absent economic incentives on capturing carbon, such as carbon tax, carbon credits carbon trade, etc., there is no clear economic justification to invest in carbon capture.

Therefore, this study will seek to calculate, inversely, the level of credit that CO_2 needs to have, or, other economic support it needs to have, in order to make the project feasible.

For quick and simple evaluation, following index are used to compare the balance between benefit and cost of the project when weighed in its net present value.

(1) EIRR (Economic Internal Rate of Return)

EIRR is derived from the equation as shown below:

$$\sum_{t=1}^{n} \frac{(B_t - C_t)}{(1 + EIRR)^t} = 0$$

where ;

"n" is the total number of years used to evaluate the project
"t" is the order of project year, 1 (one) being its first year and "n" as its last year
"B_t" is the benefit generated by project for year "t"
"C_t" is the cost incurred to project for year "t"

(2) B/C (Benefit-to-Cost) Ratio

Total benefit and total cost of the project are calculated based on its net present value over the project term. Here, B/C Ratio is total benefit divided by total cost. If the B/C Ratio is greater than 1.0, the project is deemed to be socio-economically effective.

(3) NPV (Net Present Value)

NPV is the total sum of benefit minus cost over the project term, with the value discounted for its year of generation.

6.1.2 Basic Assumptions for Calculation

Following assumptions are made in calculation.

(1) Currency conversion rate

All cost figures are converted and aligned to US Dollars. Following currency conversion rate is used for this study:

1 USD = 6.25 RMB

1 USD = 120 JPY

(2) Project evaluation term

As a demonstration project, the life of the facility and the evaluation term of the project is defined as 20 years from the commencement of plant operation.

(3) Discount rate

Discount rate for analysis of NPV and B/C ratio was set at 10%.

(4) Inflation rate

As it is difficult to correctly predict the rate of inflation over the long period of project term, inflation has not been taken into consideration for both profit and cost in the analysis.

(5) Plant operation

It will be assumed that the demonstration plant, after its commencement, will operate 8000 hours annually at its rated capacity.

6.1.3 Project Capital Cost (CAPEX)

Cost required to construct the plant has been calculated as follows:

Table 6.1.1 Capital Cost

	Unit	Case1	Case2
Capital Cost	MUSD	22.1	18.1

This includes cost in association with engineering, procurement and construction of the plant as illustrated in the preceding section.

6.1.4 Project Operating Cost (OPEX)

Following items count as OPEX to the project after its commencement.

(1) Cost of Consumed Plant Utilities

Following utility consumption has been taken into account as cost of the operation of the project, based on the amount consumed.

Table 6.1.2 Cost of Utilities

Item	Unit	Cost Rate
Steam	RMB/ton	97.236
Cooling Water	RMB/ton	0.24
Auxiliary Power	RMB/kWh	0.3602
Plant Air	RMB/m3	0.15
Demineralized Water	RMB/ton	7.2
Waste Water	RMB/ton	1.4

For both cases, as the steam for carbon capture is generated from heat of hot blast stove, steam is not externally consumed, thus cost of steam is not considered.

For both cases, total cost of utilities are in the range of 0.9 to 1.0 MUSD annually, approximately 75% of which is from auxiliary power, and 20% of which is from cooling water.

(2) Cost of Maintenance

Cost of plant operation and maintenance, including cost of necessary consumables has been considered.

(3) Cost of Depreciation

For case in which it applies, cost of plant equipment depreciation has been taken into account, with depreciation period at 10 years, and with salvage value of 5 percent.

6.1.5 Project Economics Analysis

Based on the cost as outlined above, the break-even price of CO_2, i.e. the price of CO_2 which would balance the B/C ratio at 1.0, or EIRR to equal the discount rate (10%) was sought for both Case 1 and Case 2.

The break-even price of CO_2 under this condition is as shown below.

Table 6.1.3 Break-even price of CO_2

	Unit	Case1	Case2
Break-Even CO_2 Price	USD/t-CO_2	50.8	43.1

Project cost profile of Case 1 for this condition is shown in Fig. 6.1.1, and the cost profile for Case 2 for the same is shown in Fig 6.1.2.

Similar economics analysis were made when depreciation cost was considered as asset cost instead of upfront CAPEX.

The break-even price of CO_2 under this condition is as shown below.

Table 6.1.4 Break-even price of CO_2 (When Depreciation is considered as asset cost)

	Unit	Case1	Case2
Break-Even CO_2 Price	USD/t-CO_2	39.8	34.1

Project cost profile of Case 1 for this condition is shown in Fig. 6.1.3, and the cost profile for Case 2 for the same is shown in Fig 6.1.4.

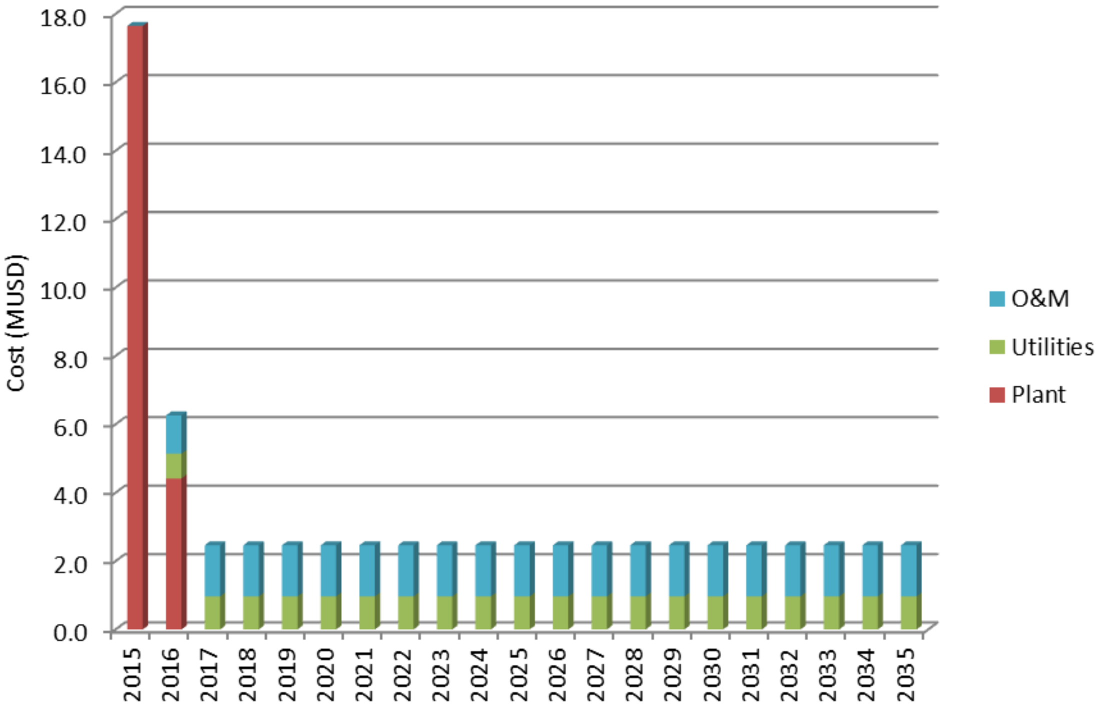

Fig. 6.1.1 Cost Profile for Case 1

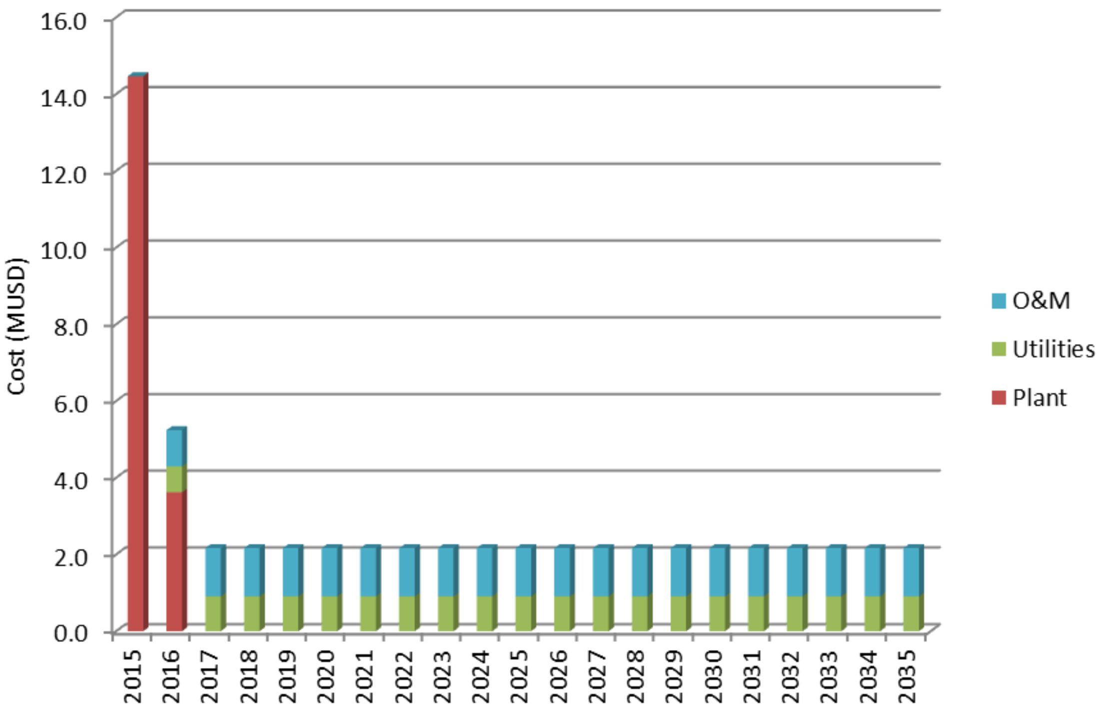

Fig. 6.1.2 Cost Profile for Case 2

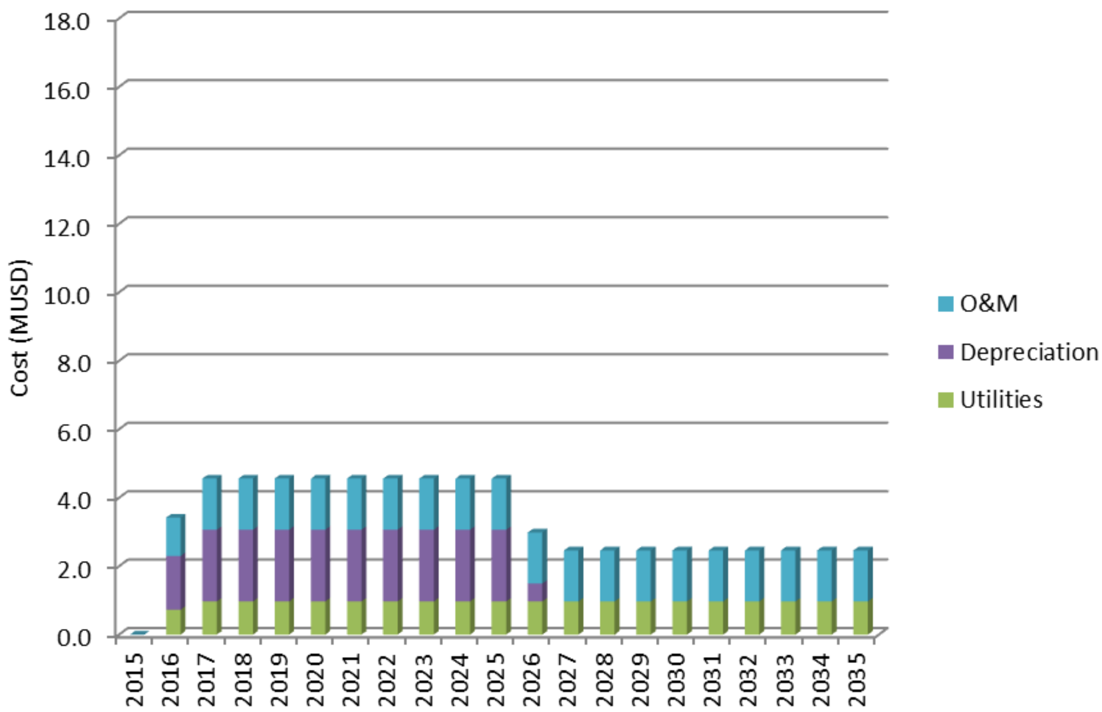

Fig. 6.1.3 Cost Profile for Case 1 (Depreciation as asset cost)

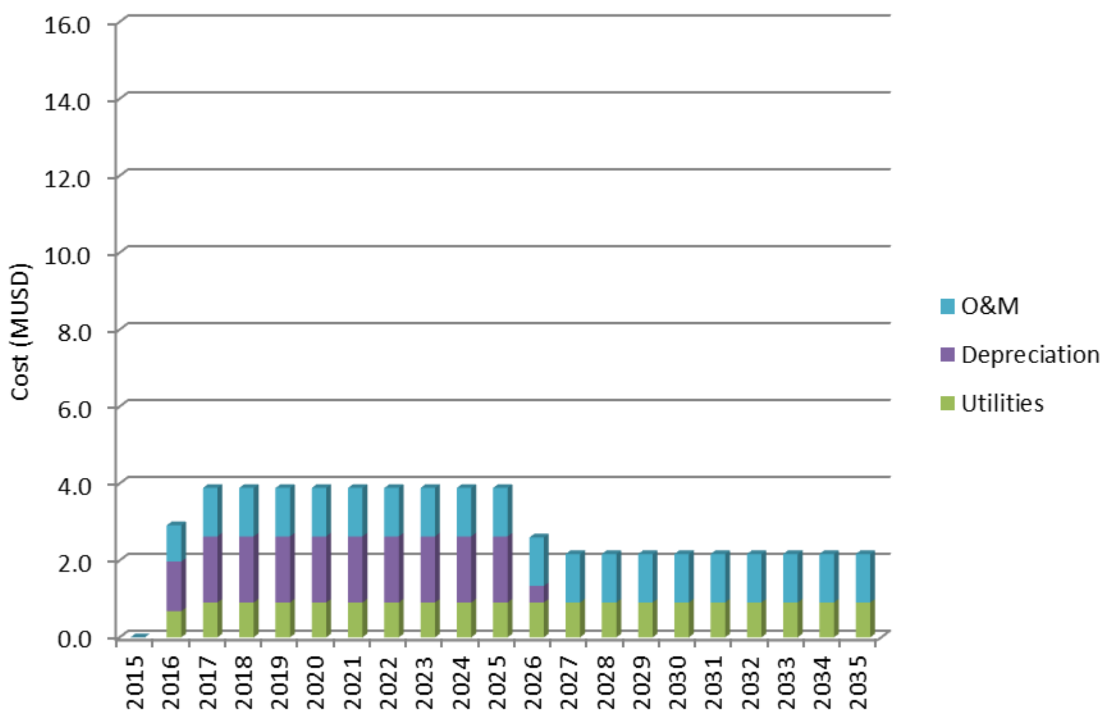

Fig. 6.1.4 Cost Profile for Case 2 (Depreciation as asset cost)

6.2 Outstanding Technical Issues

1) The technical and economics evaluation were conducted for basic condition, under the assumption that the iron and steel plant operate stably without variation or fluctuation. For further and detailed investigation. CO_2 capture plant design must take into consideration variation of the existing iron and steel plant's operating conditions, if any. This also includes future variation on flue gas composition from lime kiln and hot blast furnace, which may affect the design and operation of flue gas pre-treatment.

2) The construction of carbon capture plant should be carefully planned so as not to affect the normal production activity of Shougang Jingtang Company. Therefore, the construction schedule for interfacing between carbon capture facility and Shougang Jingtang Company's existing plant, need to reasonably take into consideration the plant's regular shutdown time.

3) Particularly for Case 1, there is a distance between the CO_2 source the lime kiln and heat and energy source the hot blast stove, and the transport distance of flue gas pipeline is long. In the actual construction of this long pipeline, there is some degree of uncertainties. The pressure losses and heat dissipation of flue gas in pipeline need to be further calculated, and the selection of exhaust gas blower and feed gas blower also need further to be verified in order to meet the system requirements and save energy.

4) Further technical investigation may be needed for effect of returning flue gas which has been captured of CO_2. For example in Case1, CO_2 removed flue gas at the absorber, which is produced by lime kiln gas, is planned to be emitted through the original chimney of the hot blast stove. It must be confirmed that it is acceptable for the chimney condition to emit the flue gas, which differs from the one planned originally.

5) Currently, the estimate of investment and operation cost of equipment for the carbon capture system, as well as required energy consumption remain comparatively high. Further work may be required to lower the cost of investment and energy consumption through combination of plant design optimization and improvement in solvent technology.

6) As illustrated in Section 3.1, 300 t/d capture facility represents only a fraction of the CO_2 emitted from the iron and steel plant, thus the constraints on the physical size of plant as well as the energy required for capture is not a major issue. If a consideration would be

required to further scale-up the amount of CO_2 capture, constraints on size as well as matching of CO_2 source of heat and energy required for capture needs to be further investigated.

7) At present, CO_2 flooding EOR technology is one of the relatively mature methods of possible CO_2 utilization for this project. However, the distance between Jidong oilfield and Shougang Jingtang Company is relatively long, which makes CO_2 transportation cost high, and there is no assured usage of CO_2 there from present to future. Active research and development of other comprehensive CO_2 utilization techniques, especially the use and application of CO_2 in steel-making process, needs to be investigated.

7. Conclusions

To answer the ever-growing need to adopt CO_2 emission reduction technology in China, the concept of applying carbon capture technology to an iron and steel industry, the third largest fixed CO_2 emitting source in China, has been investigated in this study.

The study took the example and placed focus on Caofeidian iron and steel plant, owned by Shougang Jingtang United Iron & Steel. The study identified its source gas of CO_2 as well as the heat source which may be utilized for CO_2 capture. Matching the source gas with heat source, the study explored two Cases of carbon capture plant design. Based on the data acquired from the plant, physical design and cost estimation of the carbon capture plant was conducted.

Based on the cost of plant construction as well as the cost of operation, a generic economics analysis was conducted to verify the cost of CO_2 (or the price of CO_2 which make the project economically viable). In consideration of the size of carbon capture plant, the cost of CO_2 is relatively competitive when compared against those of other countries, as well as for capture plant from other sources.

All in all, this study provides a basic overview of the possible application of carbon capture to an industrial source in China, the iron and steel plant, and illustrates that it is technically feasible. A first look at the economics of such project through this study seems promising, and thus should be further pusued through dialogue with key stakeholders and offtakers.

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[1] P. Friedlingstein, R.M.Andrew, J. Rogelj, G. P. Peters, J. G. Canadell, R. Knutti, G. Luderer, M. R. Raupach, M. Schaeffer, D. P. van Vuuren, C. Le Quéré, “Persistent growth of CO_2 emissions and implications for reaching climate targets,” Nature Geoscience, Vol. 7, p.709 (2014).

[2] CAO Yaming, ZHENG Jiapeng, LI Chenyu, FU Zhijun, SUN Guilin, SUN Rong, “Numerical Simulation and Scheme Design of CO_2 Flooding in Shallow Heterogeneous Reservoirs of Jidong Oilfield”, Journal of Oil and Gas Technology (J. JPI), Oct. 2014 Vol.36 No.10, P.157.

Attachments

Attachment 4.1.1 CCS Retrofitting Flow Diagram – Case1
Attachment 4.1.2 Major Equipment List – Case1
Attachment 4.1.3 Heat and Mass Balance – Case1 (1/2), (2/2)
Attachment 4.1.4 General Arrangement – Case1
Attachment 4.1.5 Side View (A-A) – Case1
Attachment 4.1.6 Side View (B-B) – Case1
Attachment 4.1.7 Plot Plan – Case1
Attachment 4.2.1 CCS Retrofitting Flow Diagram – Case2
Attachment 4.2.2 Major Equipment List – Case2
Attachment 4.2.3 Heat and Mass Balance – Case2 (1/2), (2/2)
Attachment 4.2.4 General Arrangement – Case2
Attachment 4.2.5 Side View (A-A) – Case2
Attachment 4.2.6 Side View (B-B) – Case2
Attachment 4.2.7 Plot Plan – Case2

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Attachment-4.1.1 CCS Retrofitting Flow Diagram - Case1

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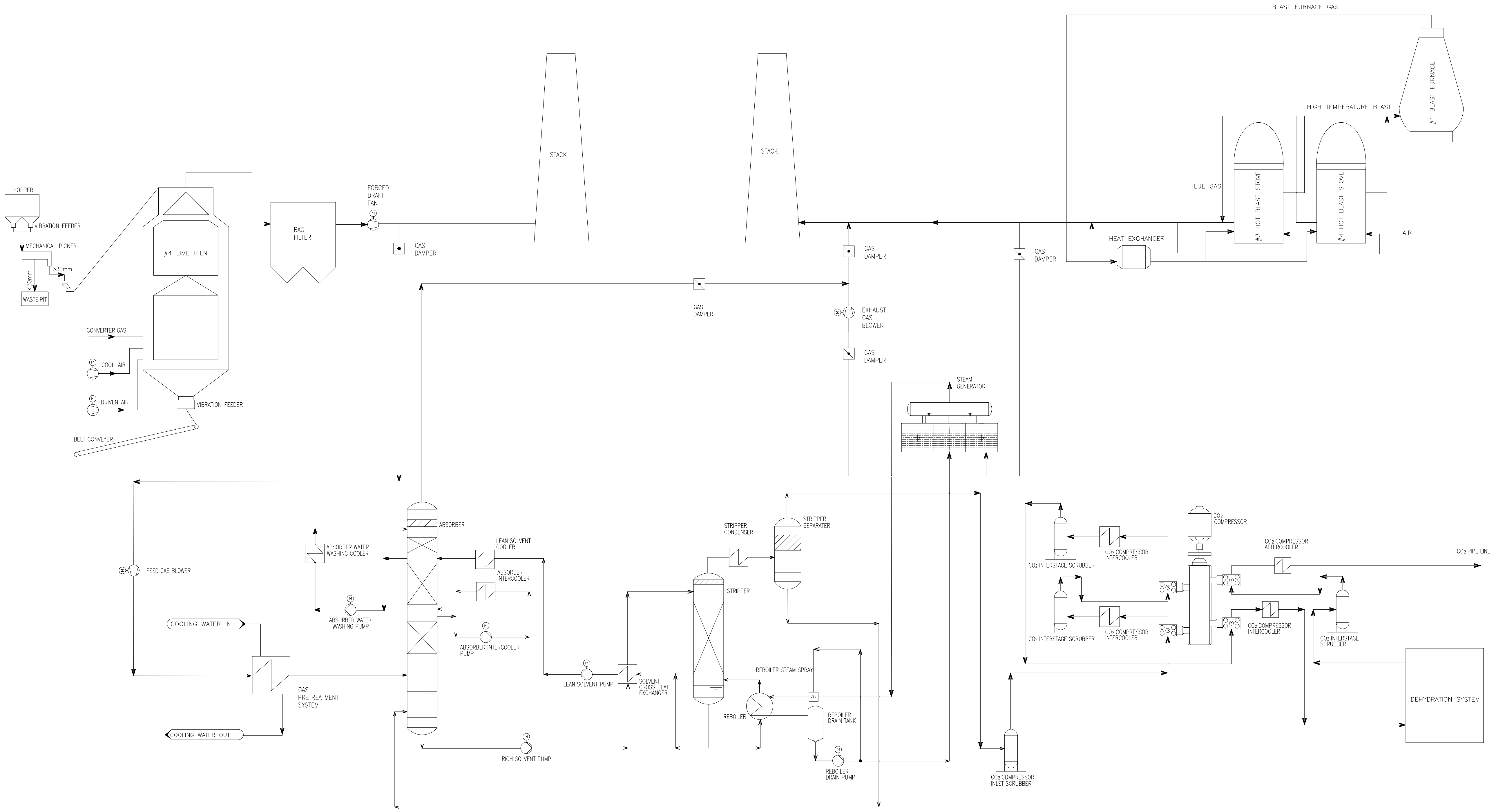
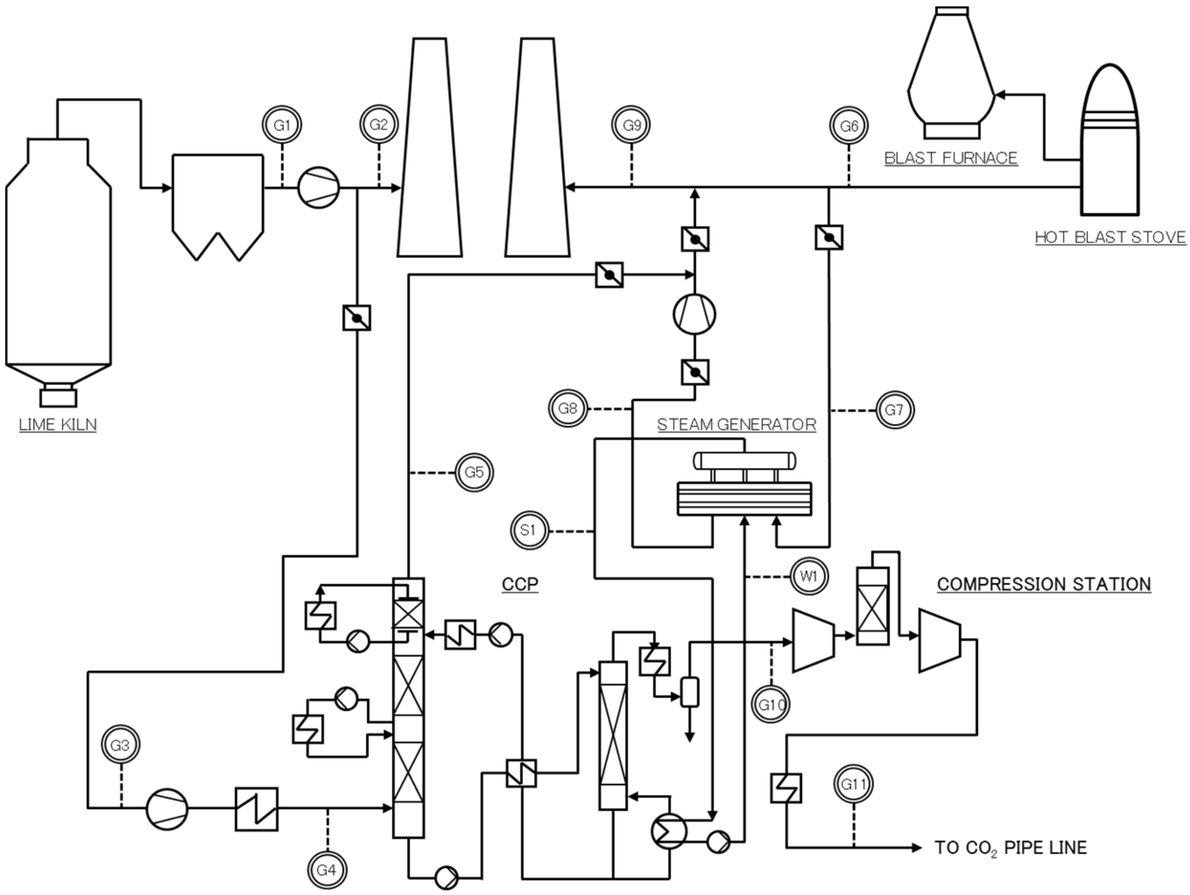


同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS for SGJT	设计阶段DES. STAGE: FS
审 定 FINAL APPR.		设计经理 PROJ. MAN.		CCS retrofitting flow diagram-Case1	
审 核 APPR.	ZhaoXudong	版 次 ISSUE			
校 核 CHKD.	SunChao	比 例 SCALE			
设 计 DES.	ZhuHong	日 期 DATE	2015.03	图 号 DRAWING NO. TFEN-E1437-C1-011	

Case1

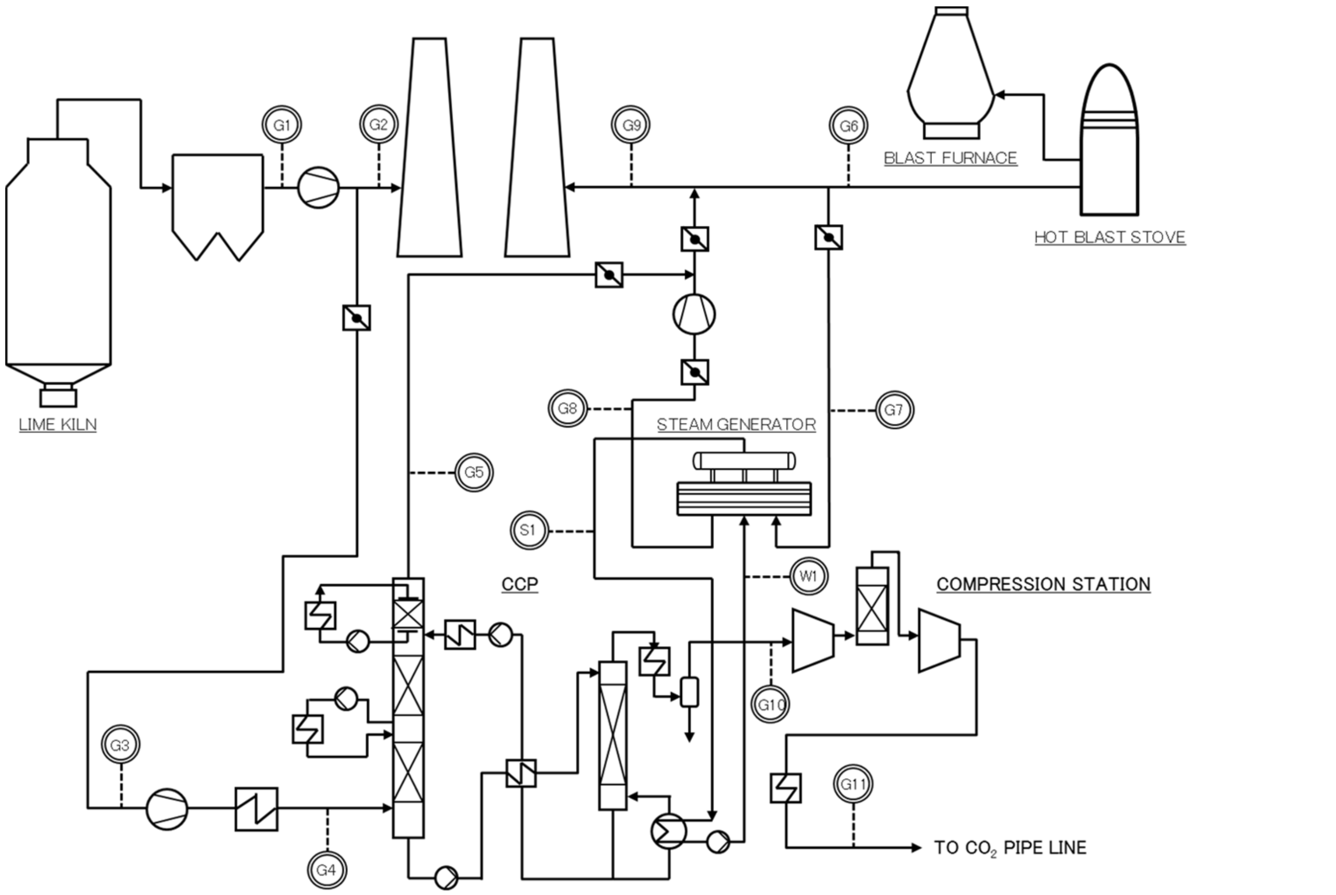
Tag No.	Equipment	System	Qty. (set)	Type	Power consumption (Per unit)
AN101	Feed gas blower	Flue gas treatment system	1	–	90
AC101	Gas pretreatent system	Flue gas treatment system	1	Shell & Tube	–
AN501	Exhaust gas blower	Flue gas treatment system	1	–	355
AP201	Rich solvent pump	CCS system	1	Centrifugal pump	90
AC201	Solvent cross heat exchanger	CCS system	1	Plate	–
AP301	Lean solvent pump	CCS system	1	Centrifugal pump	45
AC311	Lean solvent cooler	CCS system	1	Shell & Tube	–
BB001(A)	Solvent supply tank (A)	CCS system	1	Cylindrical, vertical type with agiator	–
BB001(B)	Solvent supply tank (B)	CCS system	1	Cylindrical, vertical type	–
BB011	Solvent collection tank	CCS system	1	Cylindrical, vertical type	–
AP001(A)	Solvent supply pump (A)	CCS system	1	Centrifugal pump	0.75
AP001(B)	Solvent supply pump (B)	CCS system	1	Centrifugal pump	0.75
AP002	Unloading pump	CCS system	2	Centrifugal pump	1.5
AP011	Solvent transfer pump	CCS system	1	Centrifugal pump	11
BB201	Absorber	CCS system	1	Packed tower	–
AP211	Absorber water washing pump	CCS system	1	Centrifugal pump	3
AC211	Absorber water washing cooler	CCS system	1	Shell & Tube	–
AP221(A)	Absorber intercooler pump (A)	CCS system	1	Centrifugal pump	30
AP221(B)	Absorber intercooler pump (B)	CCS system	1	Centrifugal pump	30
AC221(A)	Absorber intercooler (A)	CCS system	1	Shell & Tube	–
AC221(B)	Absorber intercooler (B)	CCS system	1	Shell & Tube	–
BB301	Stripper	CCS system	1	Packed tower	–
AC321	Stripper condenser	CCS system	1	Shell & Tube	–
BB321	Stripper separator	CCS system	1	Cylindrical	–
AC301	Reboiler	CCS system	1	Shell & Tube	–
BB501	Reboiler drain tank	CCS system	1	Cylindrical, vertical type	–
AP501	Reboiler drain pump	CCS system	1	Centrifugal pump	1.5
BB010	Demineralized water supply tank	CCS system	1	Vertical	–
AP010	Demineralized water supply pump	CCS system	1	Centrifugal pump	1.1
BB601	Industrial water supply tank	CCS system	1	Vertical	–
AP601	Industrial water supply pump	CCS system	1	Centrifugal pump	1.5
BB901	Chemical sump pit	CCS system	1	–	–
AP901	Chemical sump pump	CCS system	1	Centrifugal pump	1.1
BB911	Runoff sump pit	CCS system	1	–	–
AP911	Runoff sump pump	CCS system	1	Centrifugal pump	2.2
BB921	Waste water sump pit	CCS system	1	–	–
AP921	Waste water sump pump	CCS system	1	Centrifugal pump	1.1
BB401	Foaming inhibitor storage tank	CCS system	1	Cylindrical, vertical type	–
AP401	Foaming inhibitor injection pump	CCS system	1	Centrifugal pump	1.1
–	Vent scrubbing system	CCS system	2	Activated carbon	2.2
BB611	Cooling trough	CCS system	1	Vertical	–
AP611	Cooling water supply pump	CCS system	1	Centrifugal pump	90
AC501	Steam generator	Steam generation system	3	Vertical/Horizontal	–
AN701	CO_2 compressor	CO_2 compression and dehydration system	1	Reciprocating	2030
BB721	CO_2 surge tank	CO_2 compression and dehydration system	1	Vertical	–
BB701	Filter	CO_2 compression and dehydration system	1	Vertical	–
BB711	Dry tower	CO_2 compression and dehydration system	2	Vertical	–

Attachment-4.1.3 Heat and Mass Balance - Case1 (1/2)



		G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	S1	W1
Fluid		Flue gas from lime kiln	Flue gas from lime kiln	–	–	–	Flue gas from hot blast stove	–	–	Flue gas from hot blast stove	–	–	–	–
State		Gas	Gas	–	–	–	Gas	–	–	Gas	–	–	–	–
Pressure	kPaA	99.5	102.3	–	–	–	100.9	–	–	100.9	–	–	–	–
Temperature	℃	110.0	110.0	–	–	–	258.4	–	–	258.4	–	–	–	–
Flow rate	kg/h	105,863	105,863	–	–	–	532,192	–	–	532192	–	–	–	–
	Nm3/h	75,304	75,304	–	–	–	369,420	–	–	369420	–	–	–	–
Enthalpy	kJ/kg	–	–	–	–	–	–	–	–	–	–	–	–	–
CO2	mass.%	26.94	26.94	–	–	–	38.86	–	–	38.86	–	–	–	–
O2	mass.%	13.07	13.07	–	–	–	2.49	–	–	2.49	–	–	–	–
N2	mass.%	59.43	59.43	–	–	–	56.51	–	–	56.51	–	–	–	–
H2O	mass.%	0.57	0.57	–	–	–	2.14	–	–	2.14	–	–	–	–
CO2	vol.%	19.29	19.29	–	–	–	28.52	–	–	28.52	–	–	–	–
O2	vol.%	12.87	12.87	–	–	–	2.51	–	–	2.51	–	–	–	–
N2	vol.%	66.85	66.85	–	–	–	65.15	–	–	65.15	–	–	–	–
H2O	vol.%	1.00	1.00	–	–	–	3.83	–	–	3.83	–	–	–	–

Feasibility Study concerning
Application of Carbon Capture and Storage Facility
onto Shougang Jingtang United Iron & Steel Company's
Caofeidian Steel Plant in China
(Case1:300t/d, Without CCS)



		G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	S1	W1
Fluid		Flue gas from lime kiln	Flue gas from lime kiln	Flue gas from lime kiln	Flue gas from lime kiln	Flue gas	Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas	CO_2	CO_2	Steam	Steam drain
State		Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Supercritical	Gas	Liquid
Pressure	kPaA	99.5	102.3	102.3	103.7	102.3	100.9	100.9	100.5	100.5	203.2	10000.0	321.3	371.3
Temperature	℃	110.0	110.0	110.0	35.0	35.0	258.4	258.4	150.0	185.0	35.0	40.0	135.9	130.9
Flow rate	kg/h	105,863	54,080	51,783	51,783	39,135	532,192	309,660	309,660	571,328	12,647	12,507	14,375	14,375
	Nm3/h	75,304	38,469	36,835	36,835	30,286	369,420	214,950	214,950	399,706	6,480	6,307	–	–
Enthalpy	kJ/kg	–	–	–	–	–	–	–	–	–	–	–	2,728	550
CO2	mass.%	26.94	26.94	26.94	26.94	3.71	38.86	38.86	38.86	36.46	98.82	99.93	–	–
O2	mass.%	13.07	13.07	13.07	13.07	17.29	2.49	2.49	2.49	3.50	0.006	0.006	–	–
N2	mass.%	59.43	59.43	59.43	59.43	78.62	56.51	56.51	56.51	58.02	0.03	0.03	–	–
H2O	mass.%	0.57	0.57	0.57	0.57	0.38	2.14	2.14	2.14	2.02	1.15	0.041	–	–
CO2	vol.%	19.29	19.29	19.29	19.29	2.44	28.52	28.52	28.52	26.54	97.19	99.85	–	–
O2	vol.%	12.87	12.87	12.87	12.87	15.65	2.51	2.51	2.51	3.51	0.008	0.008	–	–
N2	vol.%	66.85	66.85	66.85	66.85	81.30	65.15	65.15	65.15	66.37	0.04	0.04	–	–
H2O	vol.%	1.00	1.00	1.00	1.00	0.61	3.83	3.83	3.83	3.59	2.77	0.10	–	–

Feasibility Study concerning
Application of Carbon Capture and Storage Facility
onto Shougang Jingtang United Iron & Steel Company's
Caofeidian Steel Plant in China
(Case1:300t/d, With CCS)

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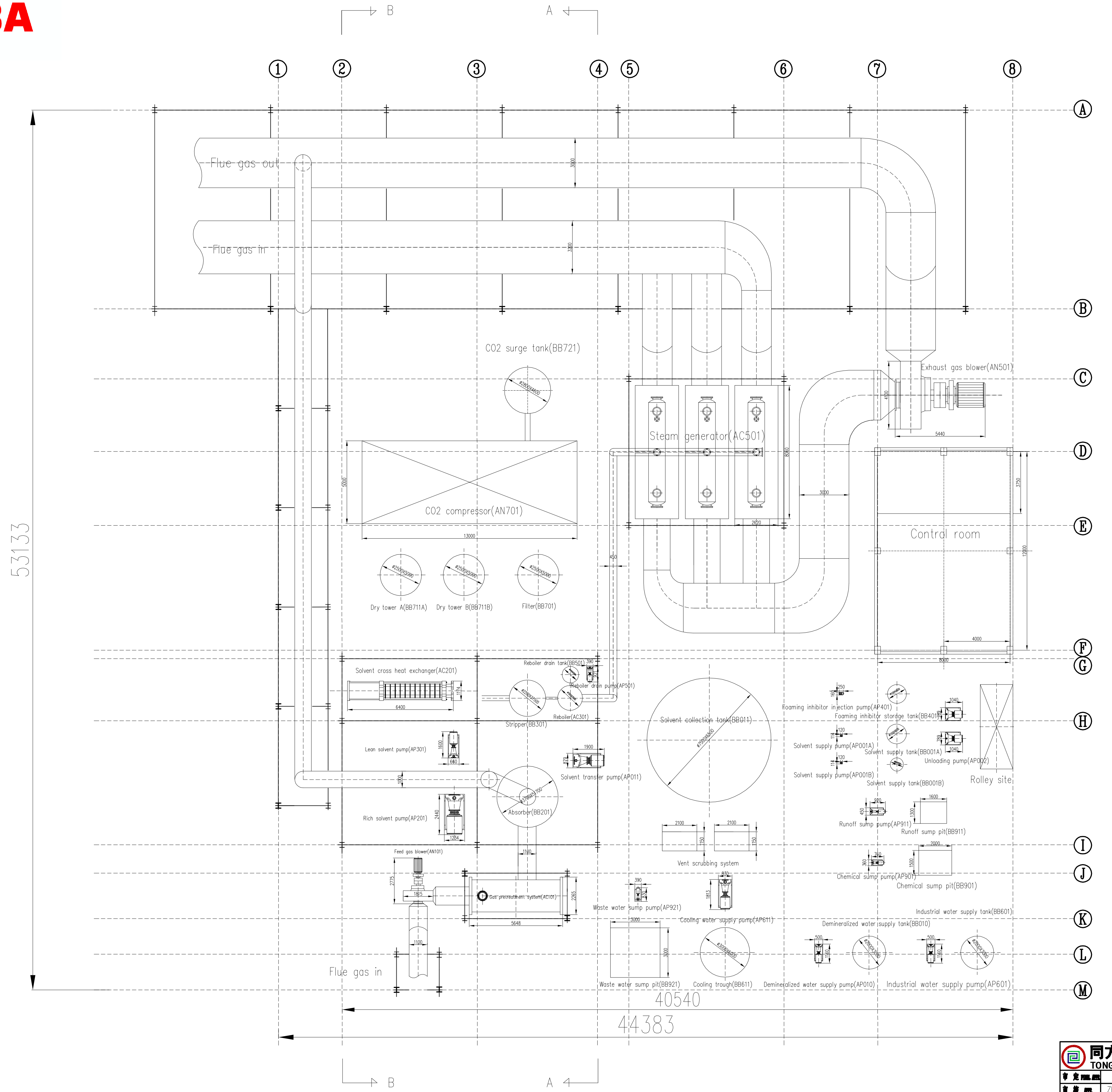
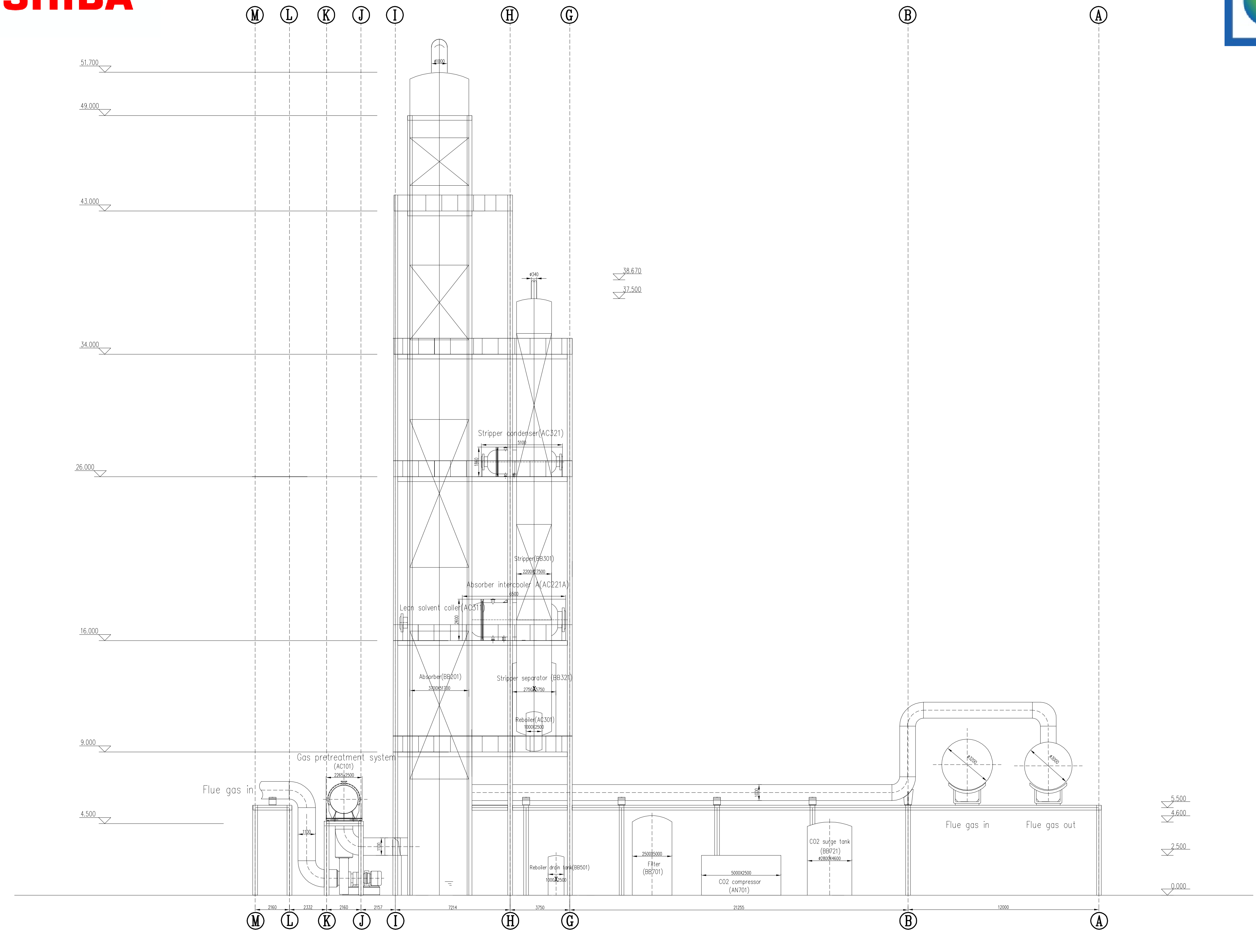
Attachment-4.1.4 General Arrangement - Case1



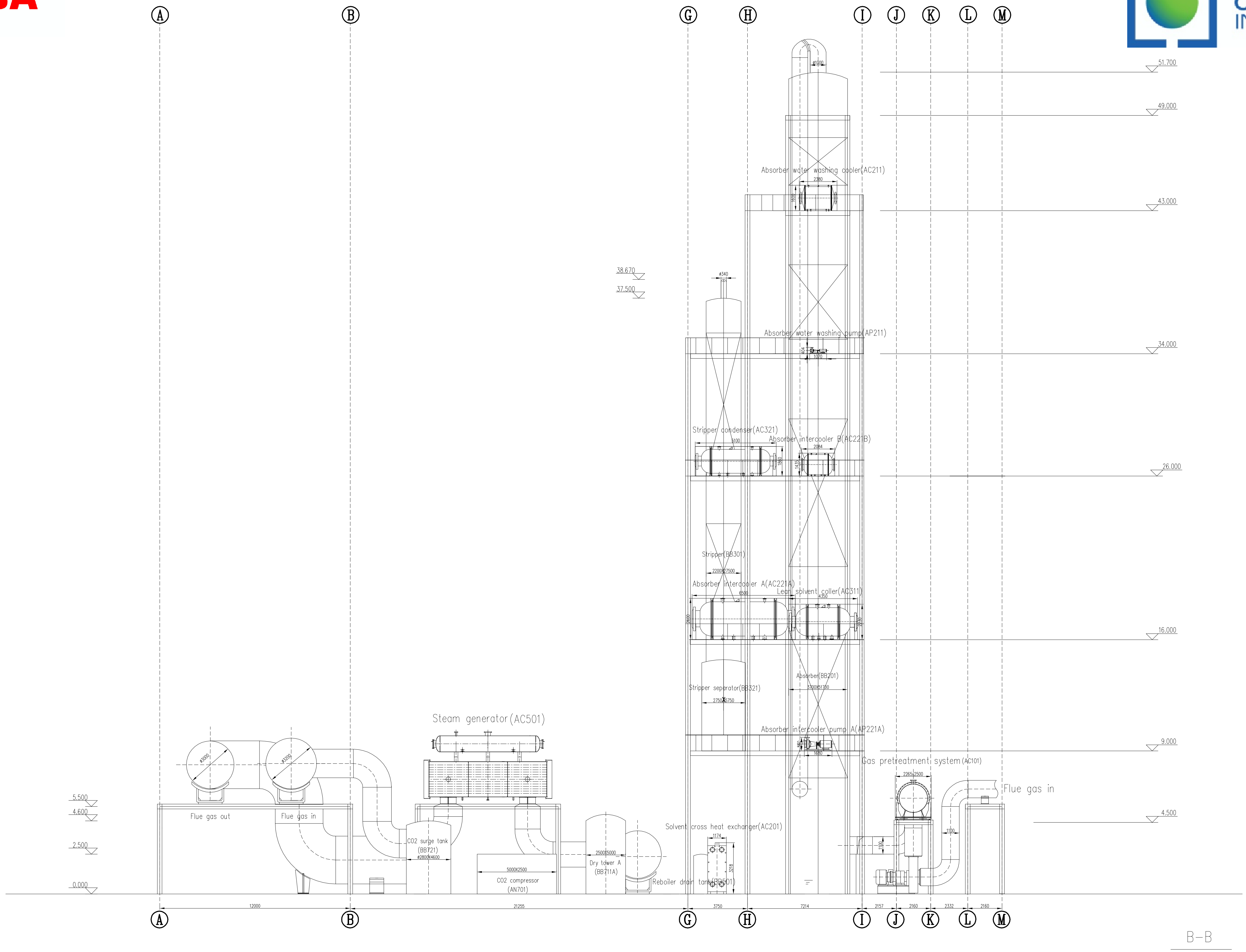
同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS about Lime Kiln Case for SGJT	设计阶段 DES. STAGE: FS
审定 FINAL APPR.		设计经理 PROJ. MGR.		General arrangement drawing of CCS by pipeline (Case1: 300t/d)	
审核 APPR.	ZhaoXudong	版次 ISSUE			
校核 CHKD.	ZhuHong	比例 SCALE	1:1		
设计 DES.	SunChao	日期 DATE	2015.03	图号 DRAWING NO.	TFEN-E1437-C1-002

Attachment-4.1.5 Side View (A-A) - Case1



同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS about Lime Kiln Case for SGJT	设计阶段 DES. STAGE: FS
审定 FINAL APPR.		设计经理 PROJ. MGR.		Side view of general arrangement (Case1: 300t/d)	
审核 APPR.	ZhaoXudong	版次 ISSUE			
校核 CHKD.	ZhuHong	比例 SCALE	1:1		
设计 DES.	SunChao	日期 DATE	2015.03	图号 DRAWING NO.	TFEN–E1437–C1–003

Attachment-4.1.6 Side View (B-B) - Case1



同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS about Lime Kiln Case for SGJT	设计阶段 DES. STAGE: FS
审定 FINAL APPR.		设计经理 PROJ. MAN.		Side view of general arrangement (Case1: 300t/d)	
审核 APPR.	ZhaoXudong	版次 ISSUE			
校核 CHKD.	ZhuHong	比例 SCALE	1:1		
设计 DES.	SunChao	日期 DATE	2015.03	图号 DRAWING NO.	TFEN-E1437-C1-014

Attachment-4.1.7 Plot Plan - Case1

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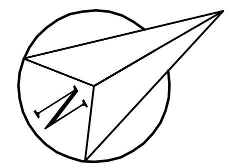
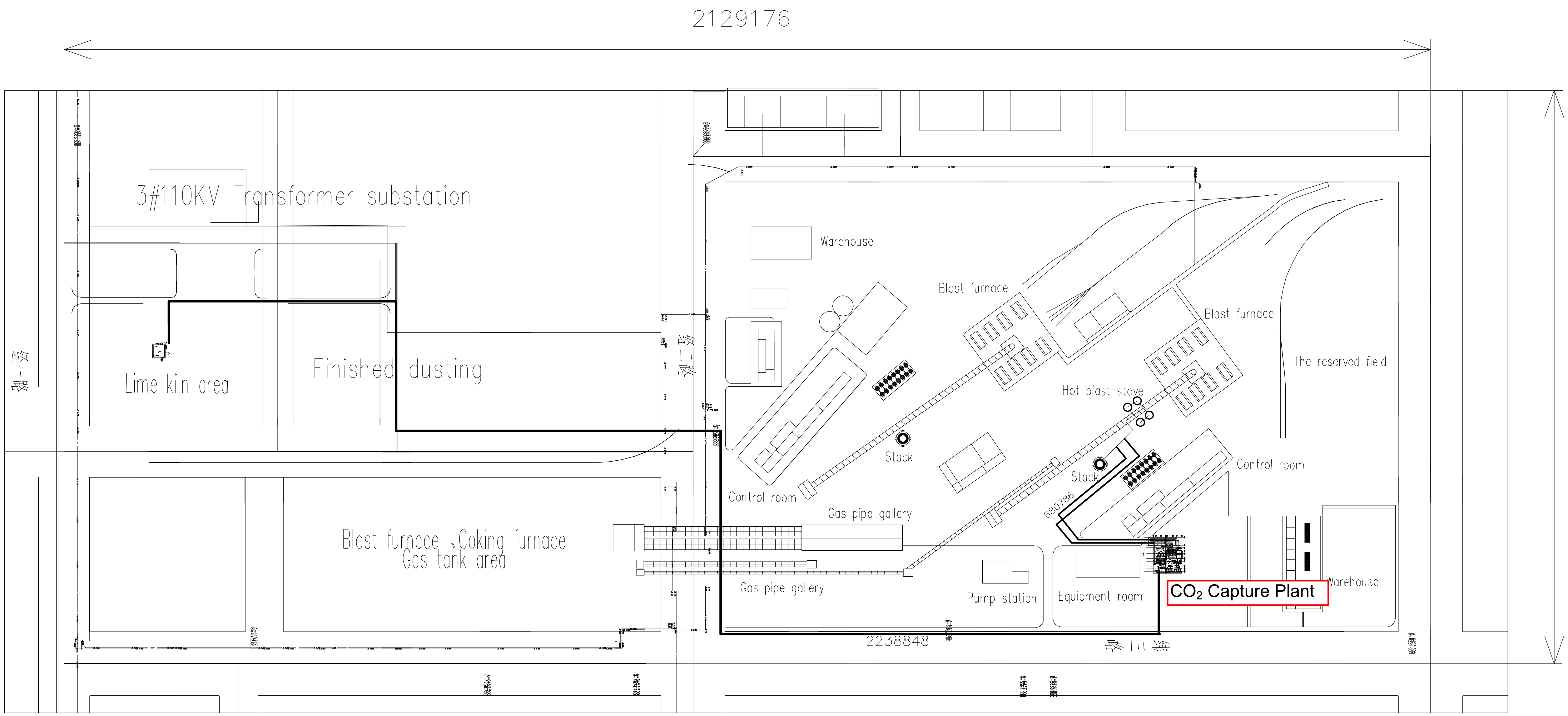
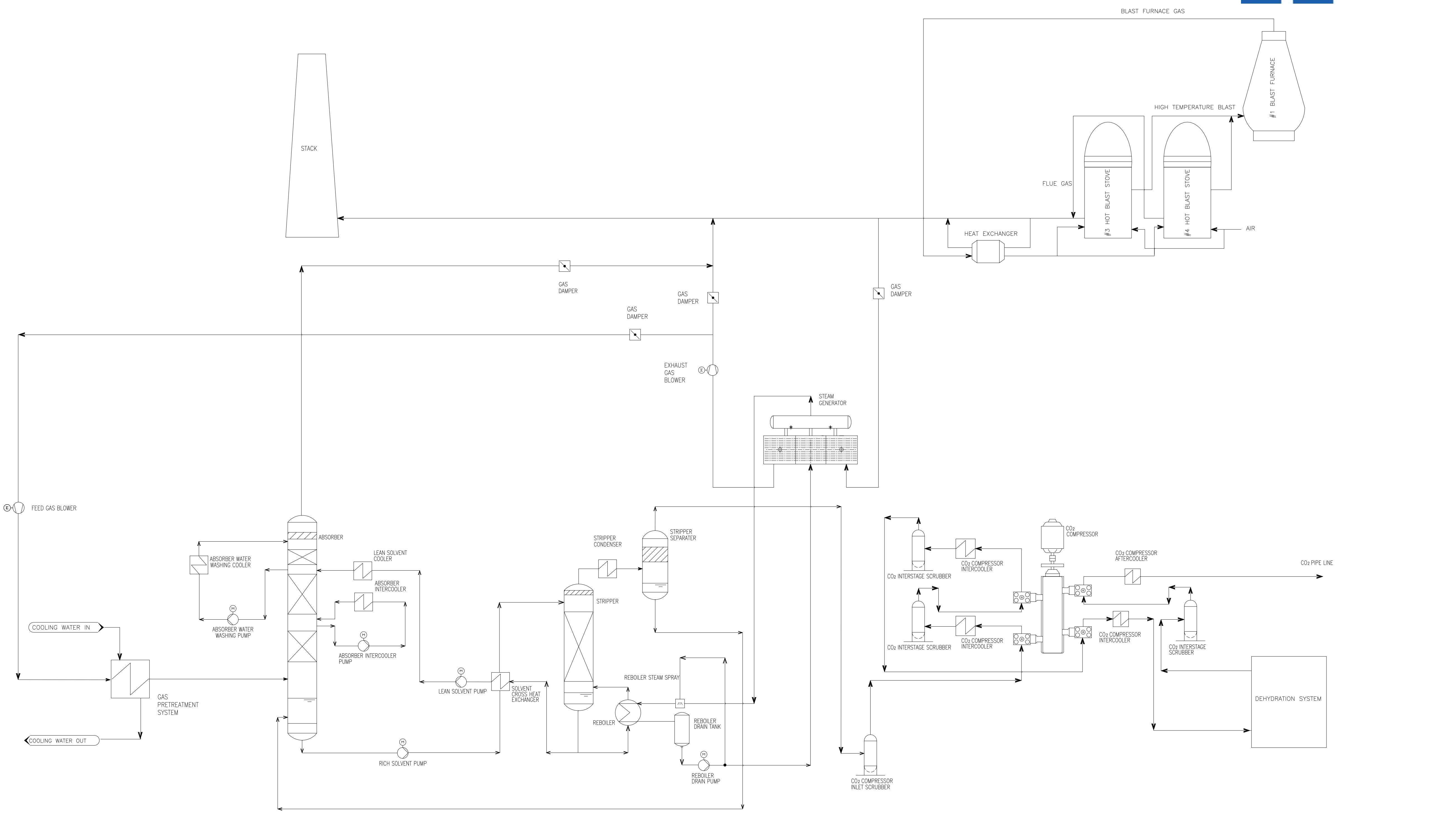




同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS about Lime Kiln Case for SGJT	设计阶段 DES. STAGE FS
审定 FINAL APPR.		设计经理 PROJ. MGR.		Plot plan of CCS for SGJT (Case1:300t/d)	
审核 APPR.	ZhaoXudong	版次 ISSUE			
校核 CHKD.	ZhuHong	比例 SCALE	1:1		
设计 DES.	SunChao	日期 DATE	2015.03	图号 DRAWING NO.	TFEN-E1437-C1-011

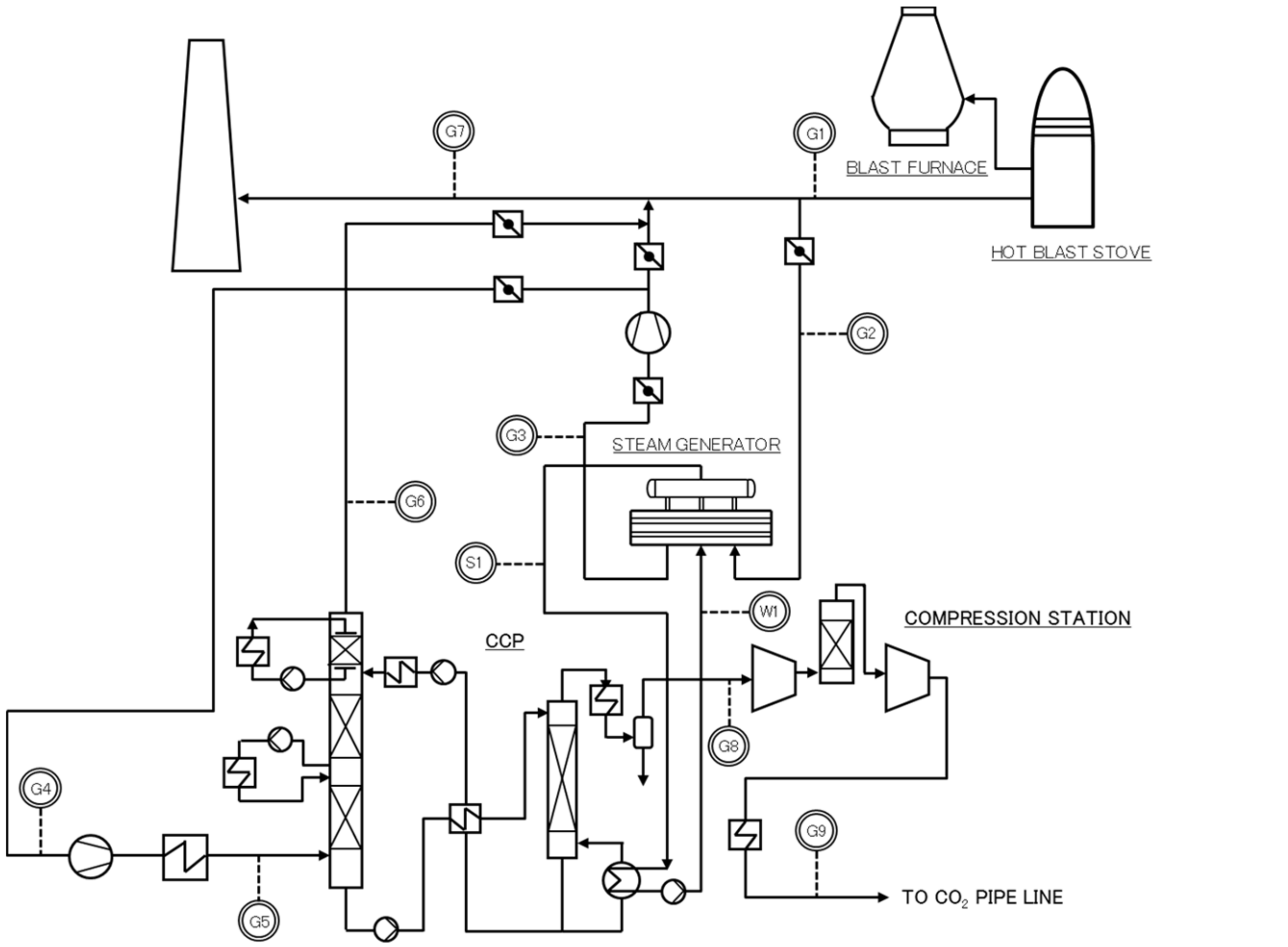
Attachment-4.2.1 CCS Retrofitting Flow Diagram - Case2



同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS for SGJT	设计阶段DES. STAGE FS
审 定 FINAL APPR.		设计经理 PROJ. MAN.		CCS retrofitting flow diagram-Case2	
审 核 APPR.	ZhaoXudong	版 次 ISSUE			
校 核 CHKD.	SunChao	比 例 SCALE			
设 计 DES.	ZhuHong	日 期 DATE	2015.03	图 号 DRAWING NO. TFEN-E1437-C2-011	

Case2

Tag No.	Equipment	System	Qty. (set)	Type	Power consumption (Per unit)
AN101	Feed gas blower	Flue gas treatment system	1	–	65
AC101	Gas pretreatent system	Flue gas treatment system	1	Shell & Tube	–
AN501	Exhaust gas blower	Flue gas treatment system	1	–	355
AP201	Rich solvent pump	CCS system	1	Centrifugal pump	75
AC201	Solvent cross heat exchanger	CCS system	1	Plate	–
AP301	Lean solvent pump	CCS system	1	Centrifugal pump	38
AC311	Lean solvent cooler	CCS system	1	Shell & Tube	–
BB001(A)	Solvent supply tank (A)	CCS system	1	Cylindrical, vertical type with agiator	–
BB001(B)	Solvent supply tank (B)	CCS system	1	Cylindrical, vertical type	–
BB011	Solvent collection tank	CCS system	1	Cylindrical, vertical type	–
AP001(A)	Solvent supply pump (A)	CCS system	1	Centrifugal pump	0.75
AP001(B)	Solvent supply pump (B)	CCS system	1	Centrifugal pump	0.75
AP002	Unloading pump	CCS system	2	Centrifugal pump	1.5
AP011	Solvent transfer pump	CCS system	1	Centrifugal pump	11
BB201	Absorber	CCS system	1	Packed tower	–
AP211	Absorber water washing pump	CCS system	1	Centrifugal pump	3
AC211	Absorber water washing cooler	CCS system	1	Shell & Tube	–
AP221(A)	Absorber intercooler pump (A)	CCS system	1	Centrifugal pump	22
AP221(B)	Absorber intercooler pump (B)	CCS system	1	Centrifugal pump	22
AC221(A)	Absorber intercooler (A)	CCS system	1	Shell & Tube	–
AC221(B)	Absorber intercooler (B)	CCS system	1	Shell & Tube	–
BB301	Stripper	CCS system	1	Packed tower	–
AC321	Stripper condenser	CCS system	1	Shell & Tube	–
BB321	Stripper separator	CCS system	1	Cylindrical	–
AC301	Reboiler	CCS system	1	Shell & Tube	–
BB501	Reboiler drain tank	CCS system	1	Cylindrical, vertical type	–
AP501	Reboiler drain pump	CCS system	1	Centrifugal pump	1.5
BB010	Demineralized water supply tank	CCS system	1	Vertical	–
AP010	Demineralized water supply pump	CCS system	1	Centrifugal pump	1.1
BB601	Industrial water supply tank	CCS system	1	Vertical	–
AP601	Industrial water supply pump	CCS system	1	Centrifugal pump	1.5
BB901	Chemical sump pit	CCS system	1	–	–
AP901	Chemical sump pump	CCS system	1	Centrifugal pump	1.1
BB911	Runoff sump pit	CCS system	1	–	–
AP911	Runoff sump pump	CCS system	1	Centrifugal pump	2.2
BB921	Waste water sump pit	CCS system	1	–	–
AP921	Waste water sump pump	CCS system	1	Centrifugal pump	1.1
BB401	Foaming inhibitor storage tank	CCS system	1	Cylindrical, vertical type	–
AP401	Foaming inhibitor injection pump	CCS system	1	Centrifugal pump	1.1
–	Vent scrubbing system	CCS system	2	Activated carbon	2.2
BB611	Cooling trough	CCS system	1	Vertical	–
AP611	Cooling water supply pump	CCS system	1	Centrifugal pump	90
AC501	Steam generator	Steam generation system	3	Vertical/Horizontal	–
AN701	CO_2 compressor	CO_2 compression and dehydration system	1	Reciprocating	2030
BB721	CO_2 surge tank	CO_2 compression and dehydration system	1	Vertical	–
BB701	Filter	CO_2 compression and dehydration system	1	Vertical	–
BB711	Dry tower	CO_2 compression and dehydration system	2	Vertical	–



		G1	G2	G3	G4	G5	G6	G7	G8	G9	S1	W1
Fluid		Flue gas from hot blast stove	–	–	–	–	–	Flue gas from hot blast stove	–	–	–	–
State		Gas	–	–	–	–	–	Gas	–	–	–	–
Pressure	kPaA	100.9	–	–	–	–	–	100.9	–	–	–	–
Temperature	℃	258.4	–	–	–	–	–	258.4	–	–	–	–
Flow rate	kg/h	532,188	–	–	–	–	–	532,188.3	–	–	–	–
	Nm3/h	369,420	–	–	–	–	–	369,420.0	–	–	–	–
Enthalpy	kJ/kg	–	–	–	–	–	–	–	–	–	–	–
CO2	mass.%	38.86	–	–	–	–	–	38.86	–	–	–	–
O2	mass.%	2.49	–	–	–	–	–	2.49	–	–	–	–
N2	mass.%	56.51	–	–	–	–	–	56.51	–	–	–	–
H2O	mass.%	2.14	–	–	–	–	–	2.14	–	–	–	–
CO2	vol.%	28.52	–	–	–	–	–	28.52	–	–	–	–
O2	vol.%	2.51	–	–	–	–	–	2.51	–	–	–	–
N2	vol.%	65.15	–	–	–	–	–	65.15	–	–	–	–
H2O	vol.%	3.83	–	–	–	–	–	3.83	–	–	–	–

Feasibility Study concerning
Application of Carbon Capture and Storage Facility
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Caofeidian Steel Plant in China
(Case2:300t/d, Without CCS)

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Attachment-4.2.3 Heat and Mass Balance - Case2 (2/2)

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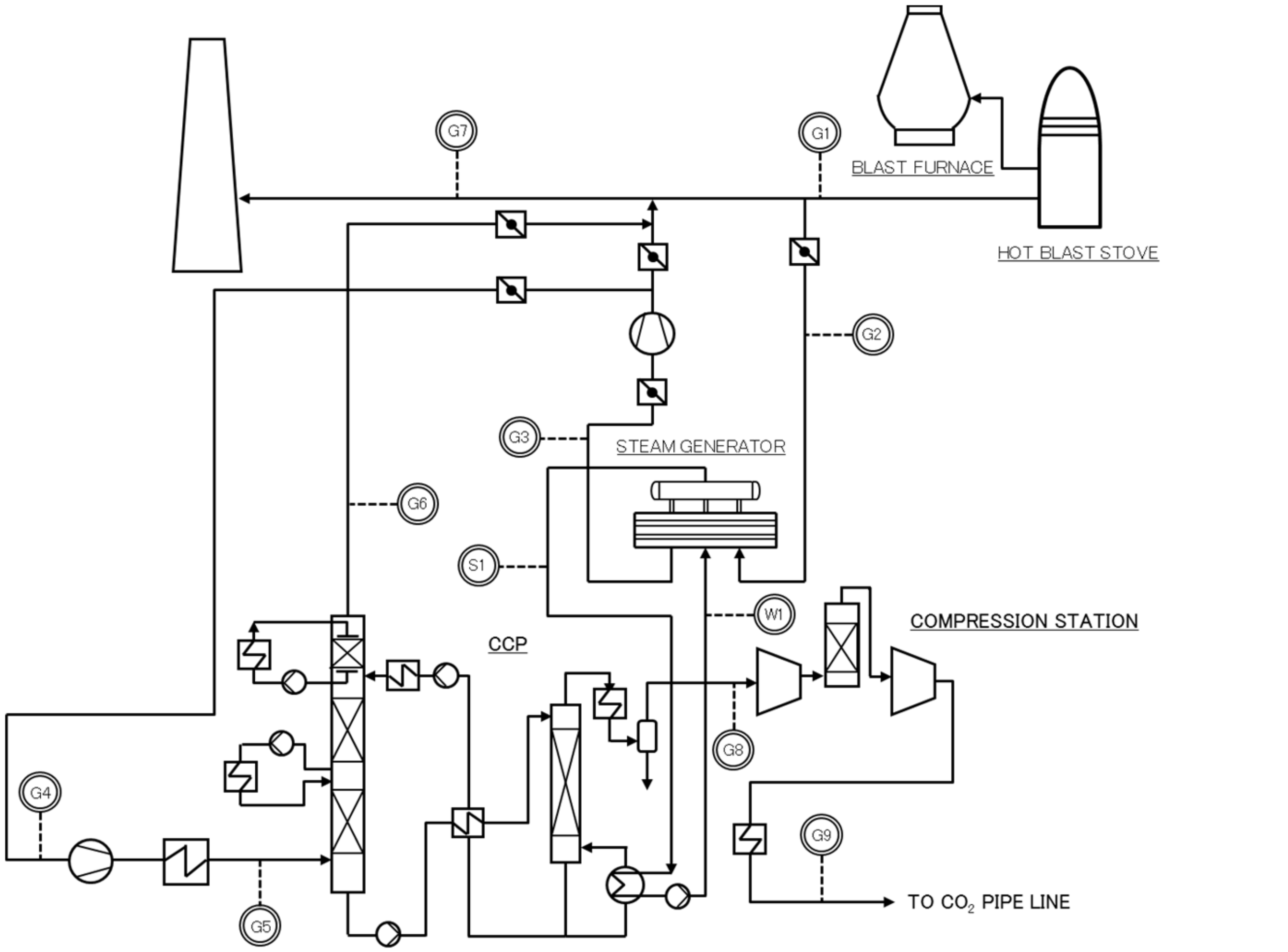
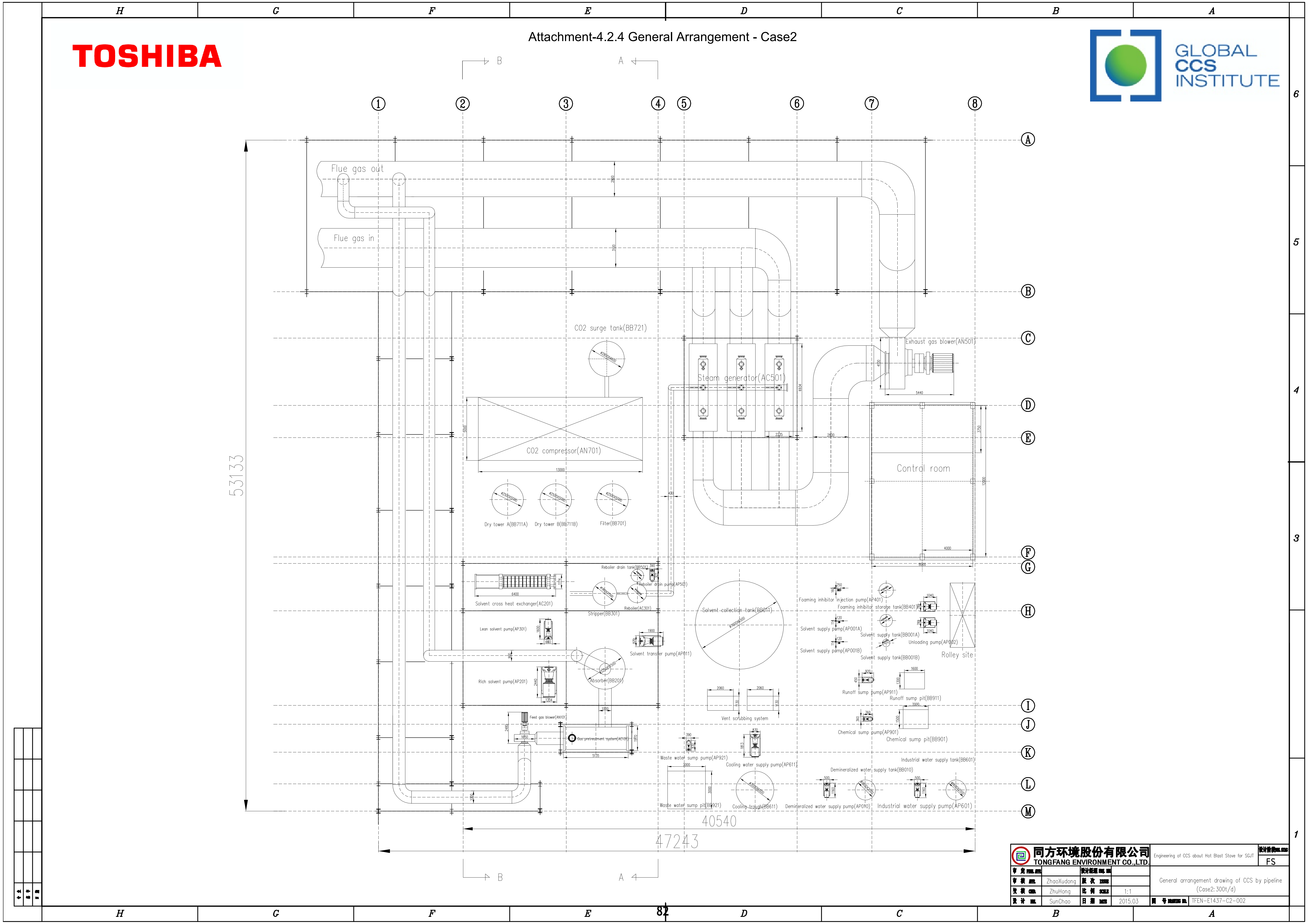


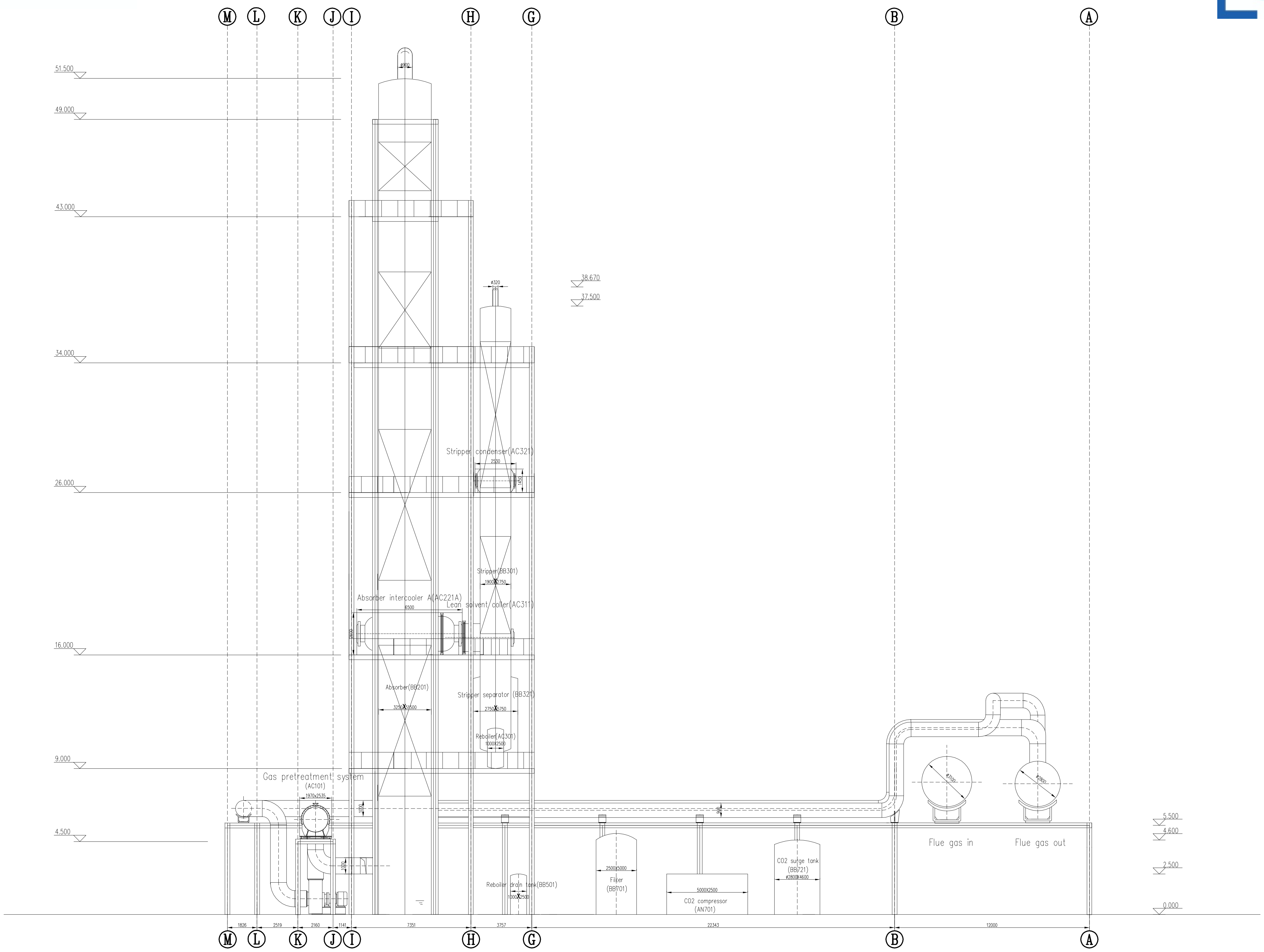
		G1	G2	G3	G4	G5	G6	G7	G8	G9	S1	W1
Fluid		Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas from hot blast stove	Flue gas	Flue gas	CO_2	CO_2	Steam	Steam drain
State		Gas	Gas	Gas	Gas	Gas	Gas	Gas	Gas	Supercritical	Gas	Liquid
Pressure	kPaA	100.9	100.9	100.5	102.2	104.0	102.6	100.9	203.2	10,000.0	321.3	371.3
Temperature	℃	258.4	258.4	150.0	155.7	35.0	35.0	197.4	35.0	40.0	135.9	130.9
Flow rate	kg/h	532,188	294,768	294,768	36,970	36,970	24,323	519,541	12,647	12,507	13,569	13,569
	Nm3/h	369,420	204,614	204,614	25,663	25,663	19,114	362,871	6,480	6,307	–	–
Enthalpy	kJ/kg	–	–	–	–	–	–	–	–	–	2,728	550
CO2	mass.%	38.86	38.86	38.86	38.86	38.86	7.68	37.40	98.83	99.94	–	–
O2	mass.%	2.49	2.49	2.49	2.49	2.49	3.78	2.55	0.001	0.001	–	–
N2	mass.%	56.51	56.51	56.51	56.51	56.51	85.89	57.89	0.02	0.02	–	–
H2O	mass.%	2.14	2.14	2.14	2.14	2.14	2.65	2.16	1.15	0.04	–	–
CO2	vol.%	28.52	28.52	28.52	28.52	28.52	4.98	27.27	97.20	99.87	–	–
O2	vol.%	2.51	2.51	2.51	2.51	2.51	3.37	2.56	0.001	0.001	–	–
N2	vol.%	65.15	65.15	65.15	65.15	65.15	87.46	66.32	0.03	0.03	–	–
H2O	vol.%	3.83	3.83	3.83	3.83	3.83	4.19	3.85	2.77	0.10	–	–

Feasibility Study concerning
Application of Carbon Capture and Storage Facility
onto Shougang Jingtang United Iron & Steel Company's
Caofeidian Steel Plant in China
(Case2:300t/d, With CCS)

Attachment-4.2.4 General Arrangement - Case2



Attachment-4.2.5 Side View (A-A) - Case2



同方环境股份有限公司 TONGFANG ENVIRONMENT CO.,LTD.				Engineering of CCS about Hot Blast Stove Case for SGJT	设计阶段 DES. STAGE
					FS
审定 FINAL APPR.		设计经理 PROJ. MGR.		Side view of general arrangement (Case2: 300t/d)	
审核 APPR.	ZhaoXudong	版次 ISSUE			
校核 CHKD.	ZhuHong	比例 SCALE	1:1		
设计 DES.	SunChao	日期 DATE	2015.03	图号 DRAWING NO.	TFEN−E1437−C2−003

TOSHIBA

Attachment-4.2.6 Side View (B-B) - Case2

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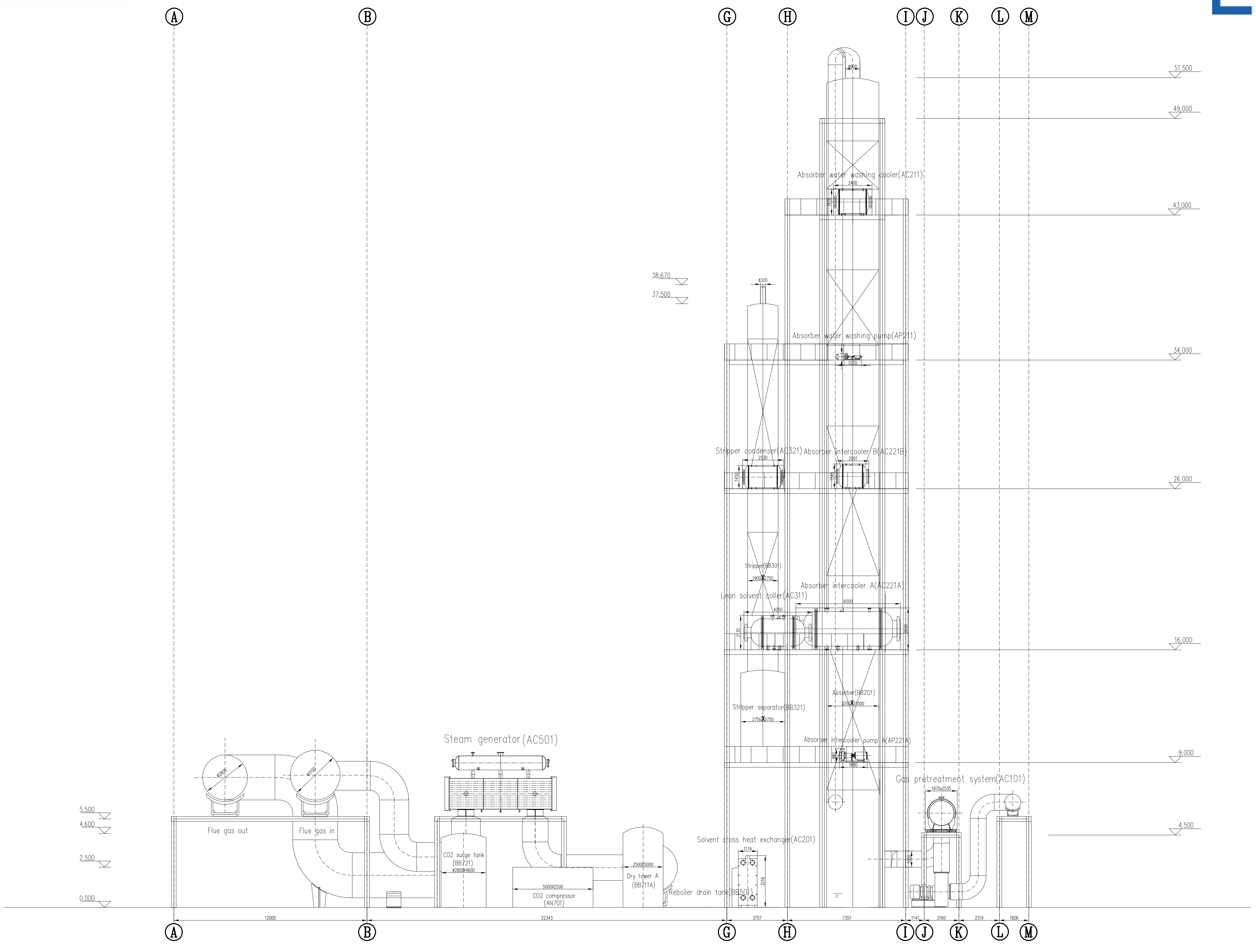

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Engineering of CCS about Hot Blast Stove Case for SGJT

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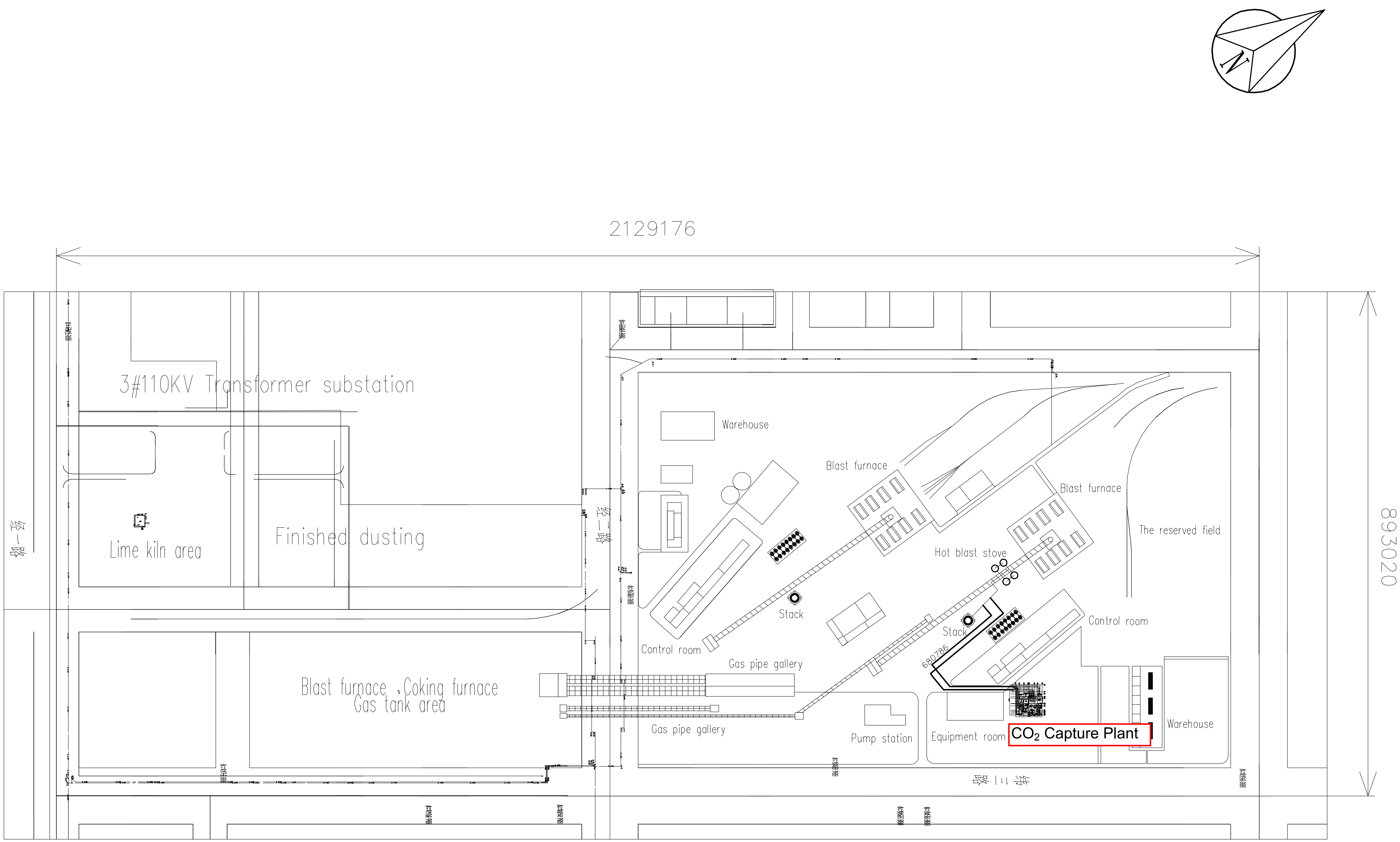
Side view of general arrangement (Case2: 300t/d)

	ZhaoXudong		
	ZhuHong		1:1
	SunChao		2015.03

TFEN-E1437-C2-014

Attachment-4.2.7 Plot Plan - Case2



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审 定		设计经理		Plot plan of CCS for SGJT (Case2:300t/d)	
审 核	ZhaoXudong	版 次 ISSUE			
校 核	ZhuHong	比 例 SCALE	1:1		
设 计	SunChao	日 期 DATE	2015.03	图 号	TFEN-E1437-C2-011