Hellfritsch, S.; Gilli, P.G.; Jentsch, N.: Concept for a Lignite-fired Power Plant Based on the Optimised Oxyfuel Process with CO Recovery. In: VGB PowerTech 8 (2004), S. 76-78

Concept for a Lignite-fired Power Plant Based on the Optimised Oxyfuel Process with CO_2 Recovery

Kurzfassung

Ein Braunkohlekraftwerkskonzept nach dem optimierten Oxyfuel-Prozess mit CO_2-Abscheidung

Durch die zukünftigen gesetzlichen Regelungen zum Klimaschutz, insbesondere die geplante Ausgabe und den Handel von Emissionszertifikaten für CO_2, werden sich in absehbarer Zeit die Betreiber von fossil befeuerten Kraftwerken gezwungen sehen, nach wirtschaftlichen Lösungen zur Senkung ihrer CO_2-Emissionen zu suchen.

Allerdings darf die in Deutschland bestehende Dominanz von Braun- und Steinkohle bei der Stromerzeugung sowie der entsprechende Bestand an modernen und leistungsfähigen Kraftwerken nicht vernachlässigt werden, daher sind auch CO_2-Minderungsmaßnahmen für den Primärenergieträger Kohle zu untersuchen.

Eine vielversprechende Möglichkeit hierfür bietet der sogenannte Oxyfuel-Prozess mit CO_2-Abscheidung. In Zusammenarbeit mit Vattenfall Europe Generation wurde am Lehrstuhl für Kraftwerkstechnik der TU Dresden ein entsprechendes Kraftwerkskonzept auf der Basis von Rohbraunkohle erarbeitet und erste Optimierungen durchgeführt.

In dem vorliegendem Beitrag werden das erarbeitete Konzept mit wesentlichen Optimierungsschritten sowie die Hauptergebnisse der bisherigen Untersuchungen vorgestellt. Hierbei wird auch ein Ausblick auf zukünftige Entwicklungsschwerpunkte gegeben.

Introduction

Near-future regulations for the German energy sector, as a key point introducing certificate trading for CO_2, will soon be forcing any power plant operating company to take measures in reducing its CO_2 emissions.

Thereby, the dominating role of coal-based power generation on the German energy market cannot be neglected since a considerable number of modern and efficient coal-fired power plants currently exist which will also be needed in future for security of supply.

The so called Oxyfuel process (O_2/CO_2 combustion process) with CO_2 separation provides an opportunity to produce electricity from carbon-rich fuels by means of a rather simple process scheme and largely available technology without emitting CO_2 into the atmosphere. As already proven by previous studies, it is possible both to retrofit existing coal-fired power plants and to apply the technology to new power plant designs.

In co-operation with Vattenfall Europe Generation, an Oxyfuel process layout for a 920 MW lignite-fired power plant was developed and optimised at the Dresden University of Technology. This work was mainly a part of an overall study comparing several methods for lignite-based electricity generation with significantly decreased CO_2 emissions into the atmosphere.

In this article the optimised Oxyfuel plant scheme with CO_2 separation is presented together with selected optimisation approaches. The main plant components and important design issues are described and an outlook is given to their future development.

Authors

Dipl.-Ing. S. Hellfritsch
Chair of Power Plant Technology,
Dresden University of Technology,
Dresden/Germany.

Professor Dr. techn. P. G. Gilli
Chair of Power Plant Technology
Dresden University of Technology
Dresden/Germany.

Dipl.-Ing. N. Jentsch
Project Manager
Dept. Technology / Basic Development
Vattenfall Europe Generation,
Berlin/Germany.

Oxyfuel Process with CO_2 Recovery Basic Description

The Oxyfuel-Process, sometimes also referred to as O_2/CO_2 combustion, is characterised by pure oxygen feeding instead of air into the combustion chamber. Since air nitrogen is excluded, it is aimed at producing a flue gas stream with up to 80 % CO_2 concentration, depending on the carbon content of the fuel.

In order to limit the flame temperature during combustion with pure oxygen, extensive flue gas recirculation into the combustion zone is necessary. Thus, the combustion throughput is increased artificially, replacing air nitrogen by recycled flue gas which mainly consists of CO_2. Figure 1 shows a basic Oxyfuel process scheme with CO_2 recovery and lignite as fuel.

The Oxyfuel process was first proposed in 1981 [6] during the emerging discussion about CO_2 as a greenhouse gas. Already at that time, experts regarded the process to as a particularly attractive option to capture the CO_2 produced by fossil-fuelled power plants. The product gas, consisting of almost 100 % CO_2 after appropriate drying and further cleaning, was suggested to be used economically in Enhanced Oil Recovery (EOR, injection of inert gases into depleted oil fields to increase the yield). After reaching full exploitation of such an oil field, it can be sealed and the CO_2 is enclosed safely. There are also other ways of storing CO_2 in a environmentally friendly way, for example Enhanced Coal Bed Methane Recovery (driving out methane from coal seams), storing it in aquifers, exploited salt deposit caverns or similar geologic formations.

One advantage of the Oxyfuel process is the relatively simple plant layout using only a few additional components coupled with the ease of almost complete CO_2 recovery. Besides CO_2, the flue gas virtually consists of water vapour only, most part of which can be extracted by condensation.

It is principally possible to retrofit conventional pulverised coal-fired steam generators with the Oxyfuel scheme. This, in fact, was also the motivation for most of the theoretical and experimental work performed so far in

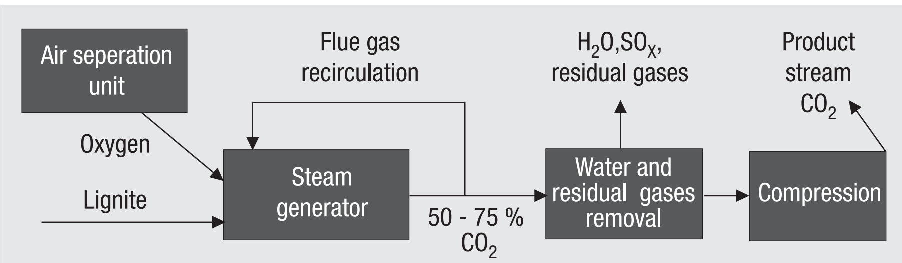

Figure 1. Principle of a lignite-fired Oxyfuel process.

this area, whereas the potential for the development of entirely new Oxyfuel plant concepts was discovered and evaluated later.

Most of these feasibility studies show promising results for the Oxyfuel process in comparison to other technologies for CO_2-free power production, especially in combination with carbon-rich fuels like coal.

Lignite-fired Oxyfuel Power Plant Concept with CO_2 Separation

At the Chair of Power Plant Engineering at the Dresden University of Technology, a novel innovative Oxyfuel concept with CO_2 separation for a 920 MW lignite-fired power plant was developed and simulated. The fuel used in this model is dried Central-German lignite (LHV raw: 11.7 MJ/kg; dried to 12 % water content: 23.0 MJ/kg) and it is assumed that the produced CO_2 has to be delivered for transportation at a supercritical pressure of 100 bar at ambient temperature.

By successively improving the internal waste heat utilisation of the power process, an optimum integration of all plant components could be obtained. Figure 2 shows the overall plant scheme with the main parameters indicated. The most important plant components will be explained in the following.

Lignite Drying Unit

In general, a higher flue gas water content increases the necessary efforts for cleaning CO_2 and also increases the low-temperature heat released during flue gas condensation. Especially when using high-moisture coal in the Oxyfuel process, as in the present case, it is therefore advantageous to use an upstream fuel drying unit. The atmospheric fluidised bed lignite drying process with internal waste heat recovery by exhaust vapour compression (WTA) is the currently most suitable solution for that problem, since the technology was already promoted to high maturity especially by the German RWE.

An exhaust vapour compression to 4.2 bar is carried out in three steps, whilst the corresponding condensate with a temperature of still 140 °C after the actual drying process is further utilised for raw coal preheating to approximately 65 °C. The final water content of the coal is 12 % by mass.

In the proposed 920 MW Oxyfuel power plant concept, provision is made for two lignite drying units in parallel to ensure sufficient availability and part load capability. It is further assumed that pre-pulverisation and particle break-up during the drying process result in particle sizes sufficiently small for pulverised coal combustion. This means that no additional coal pulverisers are assumed after the drying process.

Air Separation Unit

Cryogenic air separation units can be considered very mature and are most cost-effective for the production of large quantities of oxygen from air. A further advantage can be seen in the fact that the by-products, nitrogen and argon, can be obtained with a high purity at only low additional costs.

The principle of a cryogenic air separation is low-temperature distillation. Main part of the air separation unit is a so-called 'Cold Box', containing a highly optimised low-temperature heat exchanger, a distilling column with high- and low-pressure section and often a small expansion turbine.

Seen as a black box, which has to be constructed and optimised as a whole by the manufacturer, the following parameters can be assumed:

— incoming air at 5 to 6 bar and about 20 °C,

— outgoing oxygen at 1.5 bar and 10 to 15 °C.

These figures are valid for oxygen production with a purity of 99.6 %. Requirement for higher purities will affect the maximum system pressure (incoming air) and the investment costs, especially for the distilling column.

The air entering into the cold box has to be free of particles and water vapour in order to prevent fouling or freezing. Therefore, the air separation unit uses two molecular sieves, only one of which is in use at a time while the other one is being regenerated.

A highly optimised, multi-stage turbo compressor featuring a complex cooling system that naturally requires a large cooling water flow but therefore provides minimum power consumption usually carries out air compression.

However, this is not the main objective for successful integration into the power plant process. For the process in case, the air compression for the air separation unit is carried out in two adiabatic compression stages with intermediate cooling, so the waste heat can be recovered in a temperature range suitable for feedwater preheating which finally helps to save steam extracted from the turbine.

Of course, the manufacturer has to agree to such an unusual objective and re-defining the air compression as a substantial part of his product, since air separation units are usually delivered as standardised packages only.

To provide the amount of oxygen required for a lignite-fired Oxyfuel power plant with 920 MW gross power output, as it is referred to in this article, three of the currently largest

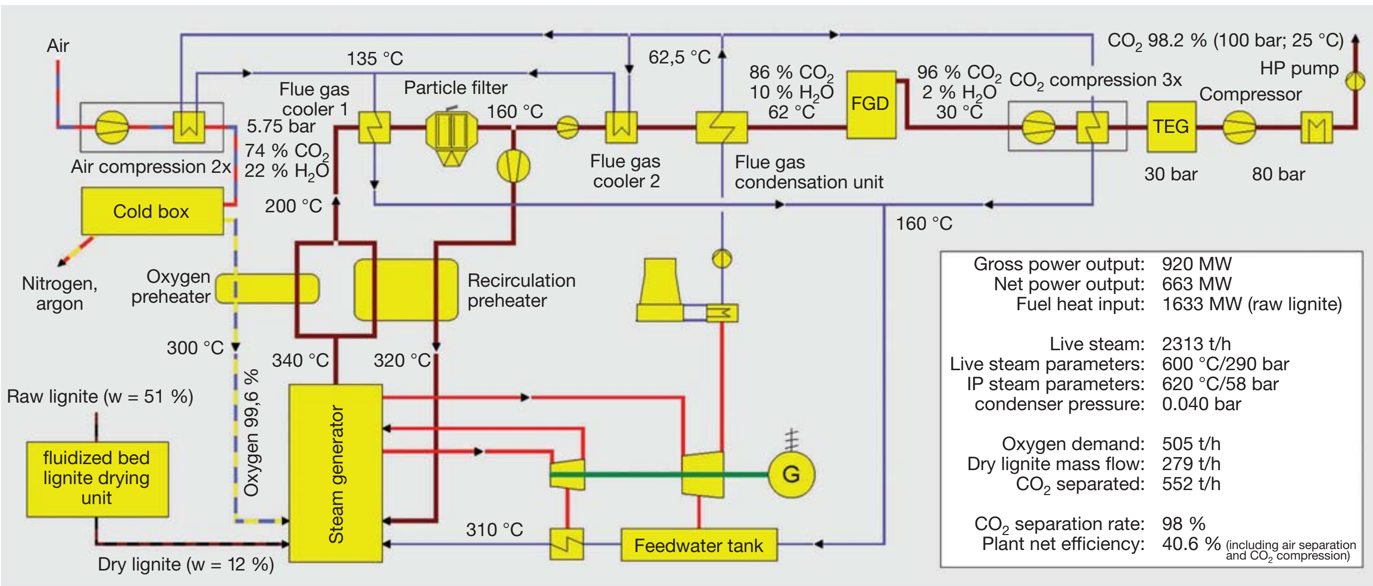

Figure 2. Process scheme of the optimised lignite-fired Oxyfuel power plant with CO_2 separation.

air separation units in the world would have to be operated in parallel. However, this does not necessarily mean a big and unacceptable rise in operation costs compared to a conventional power plant. In fact, such on-site air separation units are very reliable and can be operated with marginal costs for service and personnel especially at large scale.

An important point to be considered is the part load capability of the cryogenic air separation process, which is about 60 % for a standard package where the compressor is the limiting factor. Besides the overall power plant availability, this would be another reason for designing an Oxyfuel power plant with more than only one air separation unit.

Steam Generator

Design and engineering of the steam generator are the most important steps in the development of a coal-fired Oxyfuel power plant. A state-of-the-art lignite-fired power plant has a pulverised coal fired single pass steam generator, which was also assumed for the definition of the Oxyfuel plant concept. Other options are fluidised bed combustion with low combustion temperatures and the possibility to remove more heat from the combustion chamber, or a slag tap furnace for which the recycled flue gas flow could be greatly reduced. But whatever type of combustion, significant modifications compared to conventional boilers have to be taken into account.

Most relevant will be the tightness of the boiler, which is to prevent air infiltration and thereby dilution of the flue gas with nitrogen. That consideration does not only apply to the boiler, but also to the preliminary firing system (coal feed, burners) and all process stages in the flue gas path.

Another key point of an Oxyfuel boiler is the flue gas recirculation system. If the adiabatic flame temperature is not to exceed 1800 °C, about 75 % of the flue gas flow at the steam generator exit have to be recycled to the furnace.

However, is not correct to assume that the Oxyfuel process requires the feed of an enormous additional gas volume flow to the furnace in comparison to conventional boilers. Instead, flue gas recirculation is merely a matter of replacing the missing nitrogen from air during the combustion process. This comparison makes it obvious that the complex air feed system can be omitted and is replaced by approximately the same amount of recirculation ducts. Furthermore, the flue gas quantity after branching off the recirculation is significantly smaller than for conventional combustion with air, as shown in Figure 3.

Another characteristic of a coal-fired Oxyfuel process is the inherent NO_x reduction mechanism [4] which gives reason for the assumption that no secondary measures for NO_x reduction need to be taken (decrease in furnace height seems possible). Also the coal pulverisers and the corresponding flue gas ducts will not be necessary, if dried lignite is to be used as fuel.

The flue gas recirculation as an essential component of an Oxyfuel boiler should consist of multiple independent paths (e.g. 4 × 25 %) for security and availability reasons. Besides, the dried lignite should be conveyed pneumatically to the burners by a part flow of the recycled flue gas.

The major part of the required oxygen can be mixed into the recirculation before entering the furnace (about 30% vol.), while a small amount should be injected separately at the burner ports in order to maintain flame stability [3].

Alternative Steam Generator Types

The above-mentioned high quantities of flue gas recirculation in case of a pulverised coal-fired steam generator with dry ash removal (dry bottom) are necessary e.g. to prevent slagging.

One way to eliminate the recirculation, or at least to greatly reduce it, is a circulating fluidised bed combustion system, which enables to introduce a comparatively large number of heat exchangers in the combustion chamber (wing walls) or in the primary cycle (fluid bed heat exchangers). Thus, more heat can be transferred without a temperature rise when reducing recirculation.

As circulating fluidised bed combustion already is considered a suitable alternative for conventional power plants (France, Poland, United States, Canada), there is a chance that it has advantages in comparison to pulverised coal-fired combustion in the case of O_2/CO_2 combustion, also as the maximum size of fluidised bed combustion units has been considerably increased in recent years.

Another possibility of eliminating or at least reducing recirculation is the pulverised coal combustion with slag tap furnace, as here higher flue gas temperatures can and must be used. It usually exhibits higher NO_x emissions but this is probably a smaller disadvantage in the case of O_2/CO_2 combustion.

Boilers with slag tap furnace permit to size the steam generator smaller due to the higher temperature differences between flue gas and water/steam. So this alternative, which was in former times mainly used for hard coal, should be further investigated (e.g. concerning the increased slagging and fouling in the convective heating surfaces which has to be expected).

According to the authors´ information, lignite combustion in slag tap boilers was not successful in the past because of too low combustion temperatures, therefore dried lignite had to be used in order to keep up the tem-

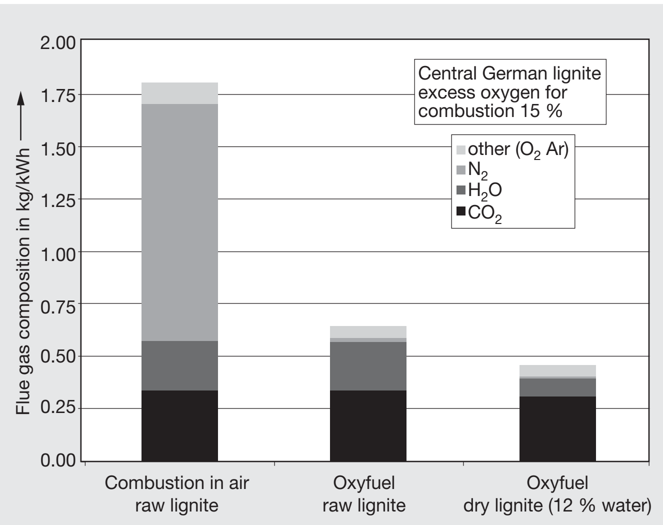

Figure 3. Quantity and composition of flue gas from different coal combustion concepts.

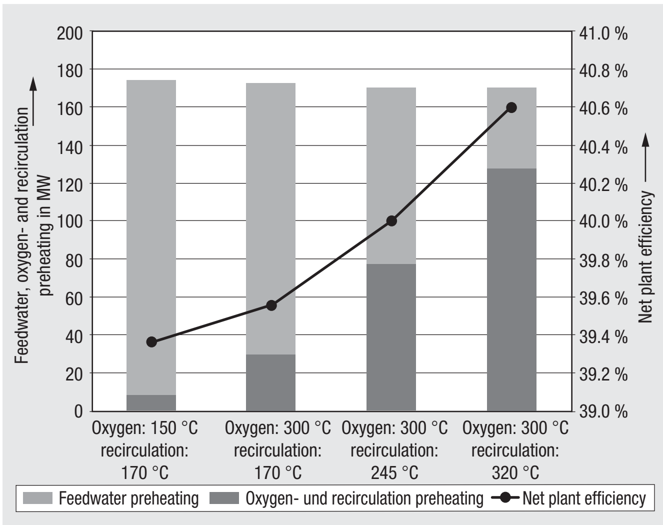

Figure 4. Efficiency enhancement by preheating oxygen and recycled flue gases.

peratures. However, this disadvantage does not apply to O_2/CO_2 combustion.

Low-temperature Flue Gas Economiser and Flue Gas Condensation Unit

The waste heat from flue gas cooling and condensation is recovered for feedwater preheating in economisers (above the dew point) and a flue gas condensation unit.

There are two preheaters installed, the larger of which will reduce the flue gas temperature from about 200 °C to 150 °C prior to entering the electrostatic precipitator, that means also before branching off the flue gas recirculation.

A smaller flue gas-heated economiser is located in the flue gas flow after branching off the recirculation; that cools the flue gases down to approximately 80 °C.

The subsequent flue gas condensation unit has to be designed acid-proof and might be compared with heat shifting systems of modern conventional power plants. During the wet process of flue gas condensation, also the bulk of SO_x and fine particles that passed the electrostatic precipitator are dissolved in the condensate.

Flue Gas Desulphurisation Plant (FGD)

During the phase of concept definition for the Oxyfuel power plant it was assumed that SO_x emissions present in the flue gas are not recommended for sequestration together with the CO_2 even independent from the type of storage that is planned. Thus, a flue gas desulphurization unit has to be included which is located downstream of flue gas condensation.

The flue gases can e.g. be desulphurised in a conventional limestone scrubbing process. It should be noted that due to the lower flue gas flow rate (after branching of the flue gas recirculation) the concentration of SO_x is higher in the raw gas since the nominal mass flow of SO_x originates from the coal. Hence, a better desulphurisation rate can be expected and at the same time the FGD plant can become smaller. The electric power consumption of the FGD unit was estimated 7.0 MW which can be considered a rather conservative assumption.

However, also other desulphurisation options could be applicable that are possibly more suitable for an Oxyfuel concept with CO_2 separation. These could be for example the Wellmann-Lord process or even the separation of SO_x together with other gaseous impurities in a distilling column. The two options mentioned are to be further investigated at the chair of power plant technology at the Dresden University of Technology.

CO_2 Compression and Final Removal of Water

After desulphurisation the CO_2 is compressed to 30 bar in three stages and dried by means of an absorbent (usually a glycol, for example TEG [2]). The drying process is followed by a further compression stage to a pressure of 80 bar. By cooling the supercritical CO_2 its properties change into a liquid-like state of high density. Gaseous impurities (oxygen, argon) remain dissolved in the product stream and a high-pressure pump provides the required transportation pressure, which in this particular case is estimated to be 100 bar.

Optimisation of Energetics and Plant Installation Engineering

Previous studies concerning lignite-fired Oxyfuel power plants with CO_2 separation, for example [2], do not consider all possible measures for integral process optimisation.

In the following it will be outlined how a net efficiency of 40.6 % for the plant concept proposed here could be obtained, whereas the maximum net efficiency for comparable optimised lignite-fired Oxyfuel processes published so far is about 34 %.

Use of Lignite Drying Unit

Fuel drying is not only an appropriate instrument for increasing the efficiency of any conventional power plant process, but has several other advantages for the Oxyfuel process: Due to the flue gas condensation, which is necessary for subsequent CO_2 treatment, in case of firing undried lignite a very large amount of low-temperature heat would be set free of which only a small fraction could be utilised in an internal heat recovery process. A lignite drying unit, ideally with internal waste heat recovery by exhaust vapour compression, diminishes the water content in the flue gas in a very efficient way. As a result, the low-temperature heat released during flue gas condensation can be utilised to a much higher percentage and thus energy losses are decreased, meaning also less required cooling capacity. In this way the heat from flue gas vapour condensation can almost entirely be recovered for internal use.

Of course there still exists an underlying optimisation problem, especially concerning the optimum resulting water content of the lignite after drying. For the current studies, lignite dried to 12 % water content by mass is used, a moisture which can be obtained by existing fluidised bed drying technology.

State-of-the-art Steam Parameters

The currently most up-to-date steam generator with live steam parameters of 275 bar/580 °C belongs to the 1000 MW BoA unit in the Niederaußem power plant of the German RWE which was commissioned in 2002.

However, taking into consideration the rapid material development during the last decade which promises even better steels in the coming years, it is by far not unrealistic to anticipate live steam pressures of more than 300 bar and temperatures of about 600 °C for the near future.

For modelling of the Oxyfuel plant in case, steam parameters of 290 bar/600 °C (live steam) and 58 bar/620 °C (intermediate pressure steam) were chosen, while the condenser pressure was set to 40 mbar assuming the use of an optimised cooling tower.

Preheaters in Flue Gas Recirculation and Oxygen Feed Stream

Most studies on Oxyfuel-based power plant concepts published so far definitely assume that the oxygen fed into the combustion process is not to be preheated, obviously in expectation of an increased flame temperature and thus the need for even more flue gas recirculation. Further, the flue gas recycle stream is always of a comparably low temperature that results from branching at a position in the flue gas path where prior particle removal was possible (usually below 200 °C, in the following referred to as cold recirculation).

To our knowledge, only one study did so far consider a hot recirculation for a coal Oxyfuel process at a temperature of about 340 °C [2]. However, no further comment was given on realisation options of such a scheme, especially concerning thermal impact on the large recycle fans required. Nevertheless, in another publication [4] the definite advantages of a hot recirculation (‘heat recirculation’) are explained, which are improved flame stability and emission behaviour. Without any doubt, some efforts will be necessary to remove most of the ash at about 350 °C in order to protect the recirculation fans.

Although these practical disadvantages resulting from a hot recirculation scheme do not apply in the same way for hot oxygen feed to the boiler, safety concerns and the earlier mentioned expectation of even higher flame temperatures will have been the reasons for never considering oxygen preheating. Thus, in previous studies it seemed logical to feed cold O_2 and cold recycled flue gases to the boiler, since obviously also the amount of recycled flue gas can be reduced thanks to the lower flame temperature.

In contrast to these assumptions it can be shown by both thermodynamics as well as process simulations that the large amounts of waste heat, mainly originating from flue gas cooling, are best utilised for boiler feed gas preheating.

For the plant concept proposed in this study, Figure 4 shows the influence of differently biasing boiler feed gas preheating within the internal heat recovery scheme on the net plant efficiency. For all cases shown there, the flue gas temperature before entering the flue gas condensation unit was the same. According to the results, a boiler feed gas temperature increased by 150 K, which in consequence also leads to a higher steam extraction from the turbine for feed water preheating, will raise the net plant efficiency by about 1.3 %. It is obvious but shall be mentioned here that the use of air preheaters at conventional power plants has a similar effect and thus the same purpose.

The more flue gas waste heat is transferred back to the boiler feed gases, the more thermal input is available for high-grade steam production. Thereby, at a constant fuel feed, more live steam will be produced which has a large enthalpy gradient for power production in the turbine.

In the other case of using the flue gas waste heat (below approximately 350 °C) for feedwater preheating, the effect will be a decreased demand for extraction steam from the turbine. However, extraction steam has already released most of its enthalpy and capability of power production (exergy). In addition, more steam now reaches the turbine outlet and will have to be condensed, which increases the overall cooling losses of the plant.

For this reason the internal waste heat recovery scheme of the Oxyfuel plant should primarily be directed to increasing the temperature of the boiler feed gases (oxygen and recycled flue gases). Furthermore, it could be proven by simulation that an increased heat input to the boiler does not essentially affect the flue gas recycle flow required in order to keep the flame temperature constant.

Based on these arguments, the Oxyfuel plant concept proposed in this study comprises both an oxygen preheater (oxygen outlet temperature 300 °C) and a 320 °C flue gas recycle feed to the boiler. To avoid the practical disadvantages of a hot recirculation scheme, the solution chosen here combines the benefits of both hot and cold recirculation. This is achieved by the introduction of an additional counter current flow heat exchanger which is called recirculation preheater. It is arranged in parallel to the oxygen preheater, that means subsequent to the economiser in the flue gas stream at a position where one would find the air preheaters of a conventional boiler.

Figure 5 shows the two main recirculation schemes – hot and cold – in comparison to the alternative using a recirculation preheater. The recirculation preheater provides the thermodynamic benefits of hot recirculation which are explained above, while it is still possible to use flue gas recycle fans in the temperature range below 200 °C and not to incorporate a separate hot gas particle removal. Instead, a single electrostatic precipitator is located in the flue gas stream at a suitable temperature of about 160 °C prior to branching off the recycle flow and warming it up again in the recirculation preheater.

Another argument for this special recirculation scheme is the fact that the heat exchanging flows – flue gas against oxygen and recycle gas – are situated fairly close to each other anyway.

Warming up of oxygen, which had to be produced before in the extensively power consuming cryogenic air separation unit, should definitely be carried out in a leak-proof heat exchanger to eliminate losses. In contrast, the recirculation preheater could be constructed similarly to the well-known design of rotating air preheaters at conventional boilers (Ljungström type).

Efficient Waste Heat Recovery Scheme for Feedwater Preheating

Waste heat recovery plays a dominant role for achieving an acceptable net efficiency of the Oxyfuel power plant concept, since the electric own consumption is noticeably higher than that of a conventional power plant of the same nominal size due to air separation unit and CO_2 compression. On the other hand, with the Oxyfuel process a greater variety of waste heat sources exist which can be beneficial if managed adequately.

This means especially the compressor intercooling of the air separation unit and of the CO_2 compression, the flue gas cooling and finally the condensation of flue gas water vapour. The latter is almost obligatory for an Oxyfuel process with CO_2 separation, since it provides the easiest measure to remove the bulk of the water content in the CO_2.

The basic objective when designing the waste heat recovery scheme for the Oxyfuel plant concept was to combine all heat sources in a way that provides maximum waste heat utilisation and thus minimum cooling losses of the plant. Nevertheless, a second intention was not to increase the complexity and number of components too far, such as branching pipes or flue gas heated feed water preheaters. That means that system integration and cost reduction were significant factors during process optimisation.

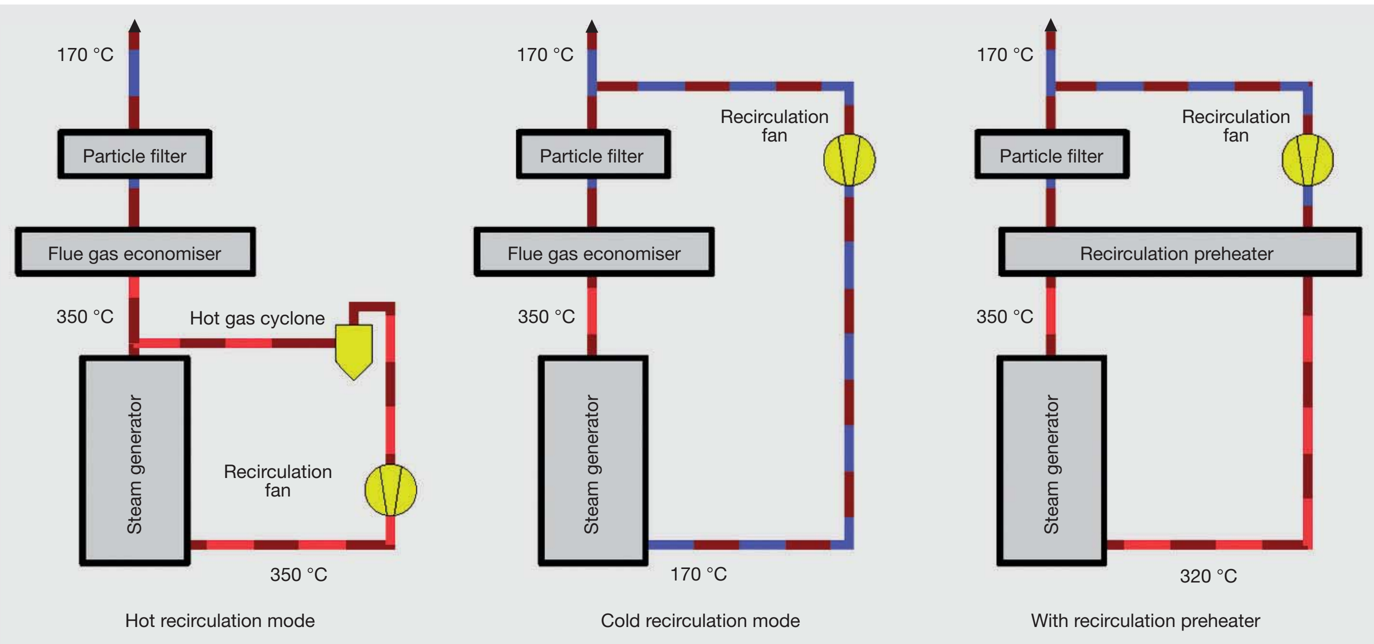

Figure 5. Comparison of different flue gas recirculation schemes.

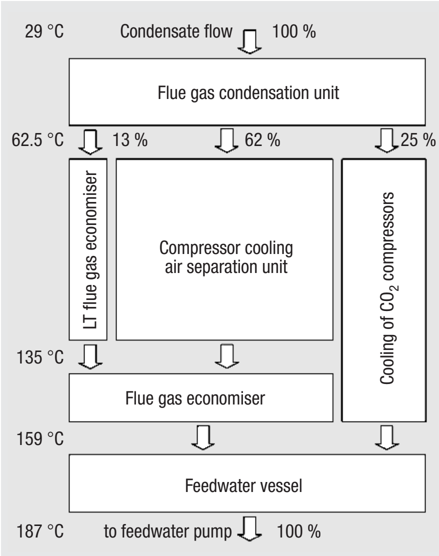

Figure 6. Feedwater preheating by internal waste heat recovery.

Figure 6 shows the optimised feed water preheating scheme. As can be seen from the flow diagram, the total feedwater stream is in a first stage led through the flue gas condensation unit for preheating. The heat released during flue gas condensation is available 'for free' but can, at atmospheric pressure, only be utilised in a low temperature range, which has a strict upper limit.

After that first stage of feedwater preheating, the feedwater stream is divided into three portions which are used for cooling the compressors of the air separation unit, of the CO_2 compression and in a smaller flue gas cooler (non-condensing) which is located behind the electrostatic precipitator in the flue gas stream. This configuration is chosen according to the finding that compressor cooling should be carried out with a minimum cooling medium inlet temperature but with largest possible warming-up temperature span.

The last stage of feedwater preheating for the two of the stream portions with the lower temperature consists of another flue gas-heated heat exchanger located prior to the electrostatic precipitator.

Introducing the feedwater preheating scheme explained above made it possible to utilise a large percentage of the waste heat generated by the plant components, such as air separation, flue gas cooling and condensing as well as CO_2 compression. Further, it can be seen from Figure 6 that obviously no low-pressure feedwater preheaters are necessary up to a feedwater temperature of about 160 °C.

Compressor Cooling Optimised for Waste Heat Recovery

The total electric power consumption of the compressors of the air separation unit and CO_2 compression is about 200 MW, which is more than one fifth of the gross power output of the plant and which is to be considered an exergetic loss at first view. Hence, a primary objective during concept definition and process optimisation was to take as much advantage as possible from the waste heat of the compressors in order to best compensate for the losses.

Temperature range and quantity of the heat recovered depend on a number of factors. First of all there is the compressor outlet temperature before intermediate cooling, which for a constant overall pressure ratio depends on the number of compression steps and the stage inlet temperature, which has a strong influence on the power consumption of the compressor. Another important factor is the amount of cooling media and its inlet temperature, which, however, can also affect the compressor stage inlet temperature.

It was defined that compressor waste heat shall only be used for feedwater preheating, since oxygen and recirculation preheating is already entirely performed using heat from flue gas cooling in the upper temperature range. Another condition was that waste heat utilisation from the several compressors is to be installed after the flue gas condensation unit, which builds the basis of the feedwater preheating scheme with the lowest temperature level.

Following these conditions, it had to be decided in which upper temperature range the compressor cooling should be installed. However, it turned out that the flue gas temperature is high enough to build the last stage of feedwater preheating and hence the compressor cooling can provide the second stage (Figure 6). Anyway it is better to provide low-temperature cooling media (corresponding to the feedwater temperature in this case) to the compressors since this enables a smaller specific volume of the compression gas resulting also in lower power consumption. In this way the basics of the feedwater preheating scheme (Figure 6) were fixed.

The next question was how many stages (with intermediate cooling) the air compression in the air separation unit and the CO_2 compression should comprise. Simple calculations show that the power consumption of compression and the compressor outlet temperatures decline with an increasing number of intercooled stages. However, it can also be demonstrated that for a constant coolant flow (for all intermediate coolers together) with a constant coolant inlet temperature the amount of recovered waste heat as a percentage of the compressor power consumption will decrease (Figure 7). In addition, the temper-

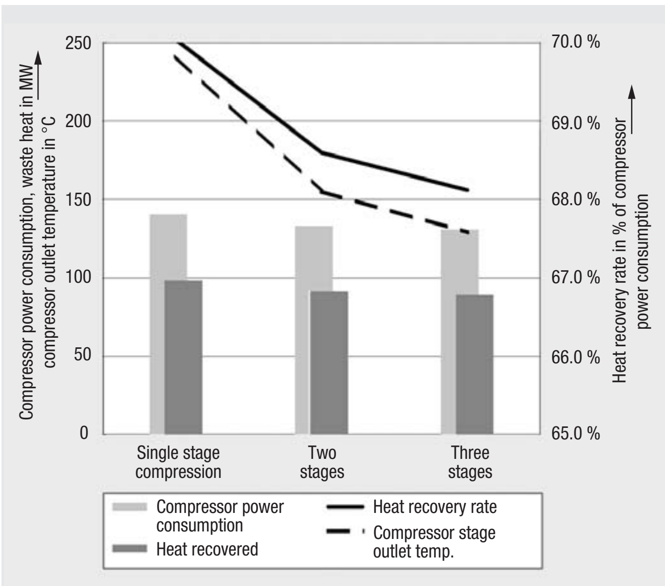

Figure 7. Variation of the number of compression stages (air separation unit).

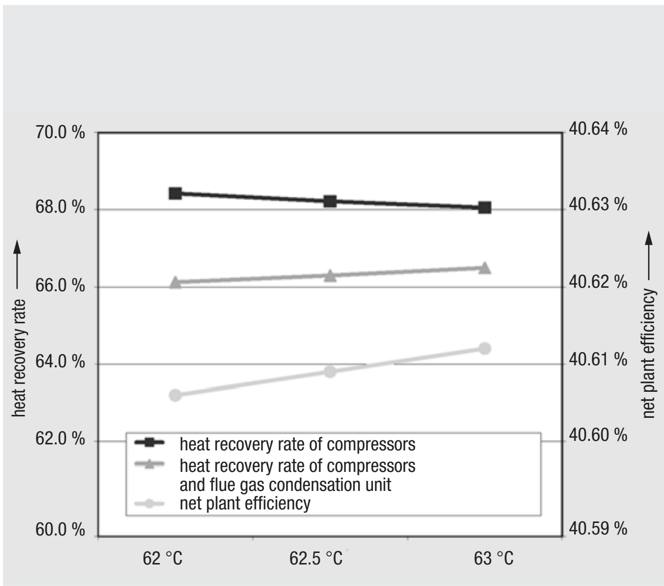

Figure 8. Variation of feedwater temperature after preheating in flue gas condensation unit.

ature range for heat recovery becomes smaller and thus the minimum required coolant flow increases.

These findings would suggest a one-step adiabatic compression for maximum heat recovery in relation to the power consumption. On the other hand, it can be seen from Figure 7 that from a certain point on the compressor stage outlet temperature is above 200 °C, which in practice leads to a higher electric power consumption and a significant drop of the isentropic compressor efficiency, even below the value of 85 % used for the simulation. Besides, there also might be some restrictions by the manufacturers for the different compressor types, so it was decided not to exceed the 200 °C limit for the process evaluation.

As a result, the air separation unit for the process in case uses a two-step compression with an overall pressure ration of 5.7. CO_2 compression from 1 to 30 bar takes place in three stages.

It shall be mentioned that the cooling water for the compressors is not the feedwater itself, but is provided by an intermediate cooling circuit.

A last optimisation approach was to decrease the cooling media inlet temperature to the compressor coolers, which primarily aimed at reducing the power consumption. It should be identified whether it is worth to loose some heat from flue gas condensation by setting a lower feedwater outlet temperature from the flue gas condensation unit, which means a lower cooling media inlet temperature to the compressor coolers and thus decreased power consumption.

However, simulations with slightly changed feed water exit temperatures from the flue gas condensation unit have shown that no improvement can be expected from that step concerning the net efficiency of the plant.

Figure 8 indicates that with reducing the cooling media inlet temperature, the heat recovery rate of the compressors alone improves, but at the same time less heat is recovered in the flue gas condensation unit, which has an even stronger influence on the net plant efficiency. It was not possible to vary the feed water temperature in a wider range, since water vapor started to condense in the intercoolers of the CO_2 compressors which caused numerical problems in the simulation software. Nevertheless, the reults in figure 8 show the correct trend concerning this design issue.

Summary

This article presented an optimised lignite-fired power plant concept that is based on the Oxyfuel process with CO_2 separation. State-of-the-art technique was used for evaluating and optimising the concept, yet a net plant efficiency of 40.6 % could be achieved at an estimated separation rate of 98 % for CO_2. Process modelling included all plant components, providing the CO_2 at a pressure of 100 bar ready for transportation. Some optimisation examples and their results are presented.

The results of the study together with internally conducted cost estimations prove that the Oxyfuel process can be a promising option for future 'CO_2-free' power generation from coal. This is based on the assumption that the price of electricity under market conditions incorporating emission certificate trading will be about 50 to 60 % above the current level.

References

[1] *Hellfritsch, S.:* Energie- und Massenbilanz für ein emissionsarmes Kraftwerk nach dem Oxyfuel-Prozess. Diploma thesis No. 1637 (Chair of Power Plant Technology, TU Dresden), 2003.

[2] *Andersson, K., Johnsson, F., and Strömberg, L.:* Large Scale CO_2 Capture - Applying the Concept of O_2/CO_2 Combustion to Commercial Process Data. VGB PowerTech 10/2003, pp. 29 - 33.

[3] *Nozaki, T. et al:* Analysis of the flame formed during oxidation of pulverised coal by an O_2-CO_2 mixture. Energy, Vol. 22, pp. 199 - 205, 1997.

[4] *Liu, H., and Okazaki, K.:* Simultaneous easy CO_2 recovery and drastic reduction of SOx and NO_x in O_2/CO_2 coal combustion with heat recirculation. Fuel, Vol. 82, pp. 1427 - 1436, 2003.

[5] *Douglas, M.A. et al:* Oxy-Combustion Field Demonstration Project. Second Annual Conference on Carbon Sequestration, Alexandria (VA), May 5 - 8 2003.

[6] *Horn, F.L., and Steinberg, M.:* A Carbon Dioxide Power Plant for Total Emission Control and Enhanced Oil Recovery, D.E.E. Brookhaven National Laboratory, 1981. □