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TITLE : Oxy-combustion : a sound CCS solution built from pilot operation

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ABSTRACT

Alstom is developing a portfolio of solutions to address CO2 emissions reduction and to support power plant owners in anticipation of emerging regulations. Among these solutions is CO2 Capture and Storage (CCS) for which Alstom is involved in the development of several CO2 capture technologies based on post-combustion and oxy-combustion.

This paper will focus on oxy-combustion and more particularly oxy-PC solutions. It is addressed to power generators that are willing to prepare their fleet for carbon reduction in the near future, using a technology that is considered as sound since the main equipment and subsystems already exist : they only need adaptation and will be proved through pilots and larger demonstration plants operation. Oxy-combustion successfully confirmed the first expectations thanks to early pilot start-up and the last 2 years of operation.

Alstom has been involved in oxy-combustion development for more than ten years. This paper will present the main results achieved during the 2 years of operation of the oxy pilots as well as the remaining challenges for the next years toward the full commercialization of large oxy-combustion power plants expected starting around 2015.

Understanding the design and control of an oxy-fired boiler is important, and Alstom has demonstrated this understanding based on the smooth operation and good performance of several oxy-fired pilots. In addition, economics of the oxy-combustion technology are very dependant on the other key components of the oxy-combustion chain : mainly the air separation unit (ASU), the gas processing unit (GPU) and their integration into the power plant.

I. Introduction

Power generation is one of the biggest source of man-made CO2 emissions. As a major supplier of equipment for this market, Alstom is developing a portfolio of solutions to address CO_2 emissions reduction and to support its clients to anticipate the future regulations. One of these solutions is CO_2 Capture and Storage (CCS) for which Alstom is developing several CO_2 Capture technologies.

There are several families of technologies under development to address CO_2 Capture are : pre-combustion (gasification), oxy-combustion and post-combustion.

The development and introduction of a new technology by its developer require a progressive scale-up with several validation steps before commercialization : small, medium pilots and large demonstration. Pursuing a strategy of developing a portfolio of adaptable capture technologies, Alstom develops post-combustion and oxy-combustion and has announced many projects and partnerships worldwide covering multiple power plants configuration, different fuels as well as different project types (new and retrofit).

This paper focuses on oxy-combustion and more particularly oxy-PC (from PC = Pulverized Coal boilers).

II. Generics on oxy-combustion and past work

Oxy-combustion is considered by a large expert community as a sound solution : main subsystems of the oxy-combustion process are proven and/or adapted from existing processes.

For the past 15 years, suppliers and power plants owners, with the support of European and North American governments have been working together to together to develop oxy-combustion technologies for the power generation market, from research and laboratory pilots up to the start-up of several large field pilots units around the world in the last two years.

The successful and smooth operation of these pilots confirm the promises of this technology as per experts expectations. As a path toward commercialization of oxy-combustion technology up to 1100 MWe scale, demonstration step will need to be validated.

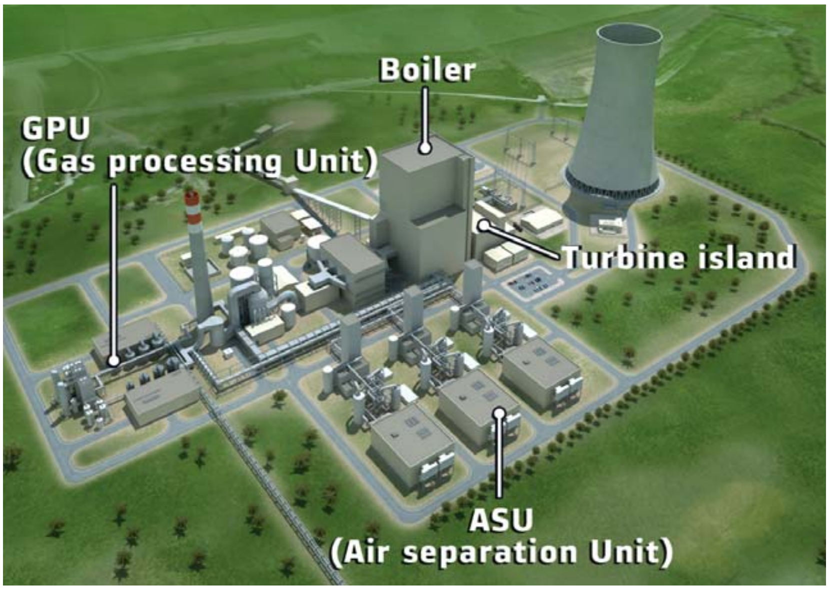
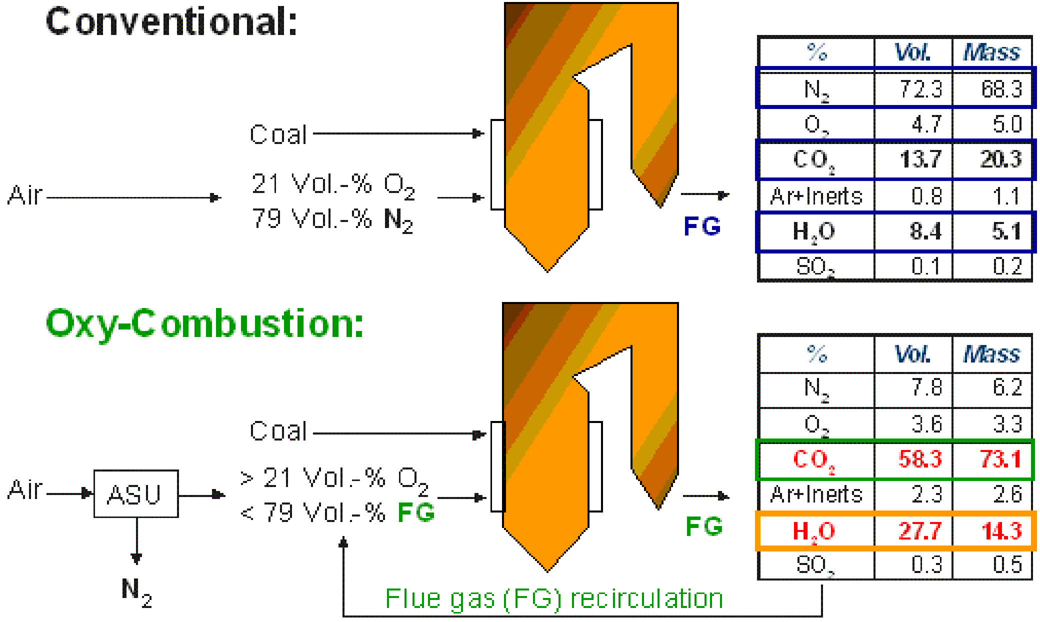


Figure 1: Aerial view of a 800 MWe-class oxy power plant

The oxy value chain (or “oxy-chain”) is composed of the following main elements : an air separation unit (“ASU”) producing pure oxygen, an oxy-boiler (burning the fuel in pure oxygen and re-circulated flue-gas instead of air), conventional Air Quality Control Systems (“AQCS”), an electrostatic precipitator (“ESP”), a Flue Gas desulphurization (“FGD”) and a Gas Procession Unit (“GPU”) including also a flue gas condenser as a first process step. A key factor for oxy-combustion process is the optimization of these components through subsystems integration : as part of balancing the trade-offs global studies are conducted to maximize the cost of electricity over the life of the plant. .For successful optimization, knowledge of new subsystems and expertise in power plant and equipment design are some of the key attributes.

In boilers with pulverized coal (PC) firing systems, the position of the flue gas extraction for re-circulation is mainly determined by the fuel quality, and in particular by the level pf coal sulfur content which determines acid dew point and corrosion potential. Such issues can be resolved by process optimization keeping sulfur compound concentrations within controllable ranges, i.e. that of conventional boilers. When using coals with low sulfur contents in PC boilers, flue gas re-circulation downstream of the dust removal of the flue gas can be envisaged. In case of higher coal sulfur contents a desulphurization of the flue gas upstream of the re-circulation makes sense in order to reduce an enrichment of the sulfur concentration in the steam generator to an acceptable level.



%	Vol.	Mass
N_2	72.3	68.3
O_2	4.7	5.0
CO_2	**13.7**	**20.3**
Ar+Inerts	0.8	1.1
H_2O	**8.4**	**5.1**
SO_2	0.1	0.2

%	Vol.	Mass
N_2	7.8	6.2
O_2	3.6	3.3
CO_2	58.3	73.1
Ar+Inerts	2.3	2.6
H_2O	27.7	14.3
SO_2	0.3	0.5

Figure 2: Simplified representation of and oxy-boiler principle as compared to conventional air-firing

The combustion of the fuel in an atmosphere of re-circulated flue gas and oxygen affects combustion behavior as well as composition and properties of the combustion products; these issues need to be considered in the design of the oxy-chain components.

A. Oxy-combustion development activities [1, 2, 3]

For more than ten years, Alstom is active in oxy-combustion development. Main activities and development roadmap is summarized in below figure 3 :

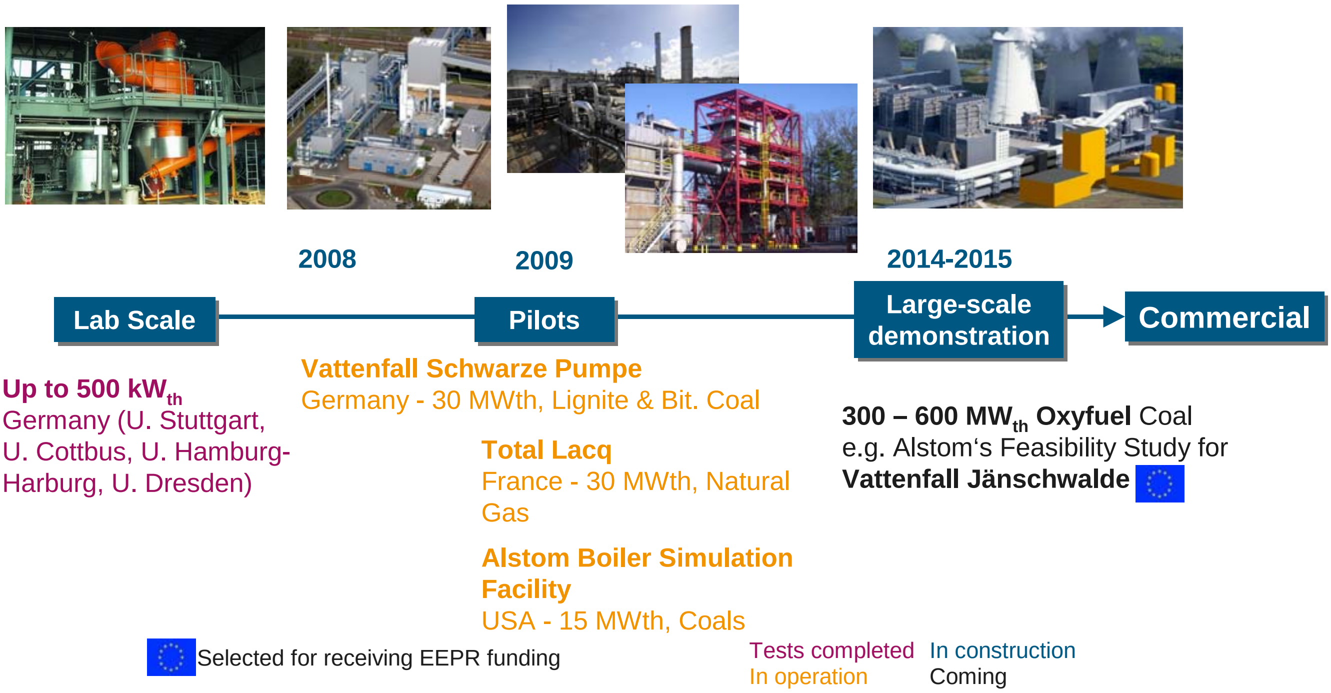


Figure 3: Alstom oxy-combustion roadmap

The initial years of development of oxy-combustion were primarily focused on the oxy-boiler development; Alstom has been involved in numerous public research projects and initiatives, some example are given hereafter : at an European level there are several projects for example ENCAP (Enhanced Capture of CO_2), OxyBurner (development and optimization of a burner for oxy-combustion conditions) and OxyCorr (investigation of material behavior under oxy-combustion conditions). The different German research programs are for e. g. ADECOS I & II (Advance Development of the Coal-fired oxy-combustion Process with CO_2 Separation) as well as recent studies show the Oxy-Combustion process in the scope of Phase II of the KW21 research initiative of the States of Baden-Württemberg and Bavaria. In these programs the combustion-specific fundamentals of the oxy-combustion process were investigated at the laboratory scale and in research plants up to a thermal output of 500 kW. The results of these investigations were the basis of the construction of the field pilot plants.

Alstom Power has also been involved in three pilots based on Oxy-Combustion technology that are operational :

- Schwarze Pumpe, 30 MWt lignite pilot plant by Vattenfall, in Brandenburg, Germany.
- A 30 MWt oxy-firing demonstration project developed by Total in Lacq-France, Alstom retrofitted an existing old boiler to natural gas oxy-combustion. The pilot started its operation under oxy-conditions in July 2009 and will be under test for two years. It is the first integrated capture, transport and storage unit in Europe. The captured CO_2 is transported over a 30 km pipe and stored in a depleted gas field in the region of Lacq.
- A 15MWt oxy-combustion boiler simulation facility at the Alstom Power Plant Laboratory (PPL) in Windsor, CT, USA.

B. The Schwarze Pumpe pilot plant of Vattenfall [1 to 10]

The Schwarze Pumpe pilot plant of Vattenfall is the first CO_2 capture field pilot covering the full oxy-chain including the ASU, a new oxy-boiler, AQCS (Air Quality Control Systems) and a GPU. Located in Germany close to an existing large coal-fired power plant, the pilot plant burns lignite as primary fuel (through indirect firing system). Some tests with bituminous and co-firing of biomass are also considered.

Alstom supplied the oxy-combustion steam generator that is shown in Figure 4, as well as the electrostatic precipitator and other ancillary systems. In addition, Alstom as technology partner of Vattenfall participates in a comprehensive test program. Construction works of the pilot plant started in October 2007. The pilot plant was in operation in September 2008.

Figure 4: oxy-boiler pilot built by Alstom in Schwarze Pumpe

On September 2008 the feasibility of the technology was demonstrated at the medium pilot plant scale with the commissioning of the complete technology chain and the capture of CO2. Since December 2008 the pilot plant has been in test operation with two Alstom burners, and as of March 2010, 6,400 total operating hours were reached, of which 2,400 h were in air mode and 4,000 h were in oxy-combustion mode. During that period 3,200 tons of CO2 have been captured. Testing with the Alstom burners will continue in January 2011.

C. 15 MWth oxy-combustion tangential firing system test facility of Alstom in Windsor, CT, USA

- Alstom is conducting a comprehensive test program to develop tangentially fired (T-fired) oxy-fuel technology for new boilers and retrofitting existing boilers. Central to the program is testing in Alstom’s 15 MWth T-fired Boiler Simulation Facility (BSF) in Windsor, CT. Testing is designed to provide detailed information on oxy-combustion behavior and the implications on boiler design and operation.

The project was initiated in September 2008 and is supported by the US DOE, a Utility Advisory Group, the States of Illinois and North Dakota, as well as other organizations. Following initial oxy-combustion process screening studies and CFD analysis of various oxy-firing system design options, test facility requirements were establish and modification for oxy-combustion testing implemented.

BSF modifications for oxy-fired testing were completed in August 2009.

Figure 5: BSF after oxy-firing modifications

The pilot-scale testing started in September 2009. Test campaigns have been completed on both subbituminous and bituminous coals. Additional test campaigns will be conducted with high sulphur bituminous coal and lignite.

The first BSF test campaign was with Powder River Basin (PRB) subbituminous coal, and included more than 200 hours of operation, during which time more than 500 tons of test coal were fired. The test plan was refined and testing conditions established based upon the results from the CFD simulations conducted under the screening evaluations. Test variables evaluated included gas recycle take-off location, gas recycle flow rates, oxygen injection flow rates and locations, windbox design, and over-fire air compartment design. Oxy-combustion development : achievements and next steps

D. RESULTS FROM MEDIUM OXY-COMBUSTION PILOTS

In the following sections an overview of the performed measurements as well as the main results from the operation of both above-mentioned oxy-combustion pilots are given in brief. First results were already published. In addition to logged operating data, probing measurements as well as solid and gaseous sampling were conducted during most test points to provide additional information on behavior. Detailed planar mapping of furnace gas temperature and gas species distributions as well as total and radiant incident heat flux to the furnace wall were conducted during long-term air- and oxy-firing tests.

The pilot results and learnings are used in the design of the demonstration units that will be the next step before commercialization.

Measurements performed during the testing at the different pilots included:

- Online Data Acquisition – logging of all major flows rates, process temperatures, pressures and gaseous compositions
- Furnace heat transfer measurements and analyses – heat absorption rates
- Deposition and corrosion probes – collection and analysis of deposits and probe metal specimens for further evaluation
- Radiant and total heat flux probe measurements at various furnace wall locations
- Fly ash loadings and samples for analysis
- High velocity suction pyrometer – for furnace temperature distributions
- Detailed furnace mapping (planar temperature and gas species distributions at various furnace elevations) at selected operating conditions
- Mercury, trace metals, and SO_3 measurements at selected points and conditions

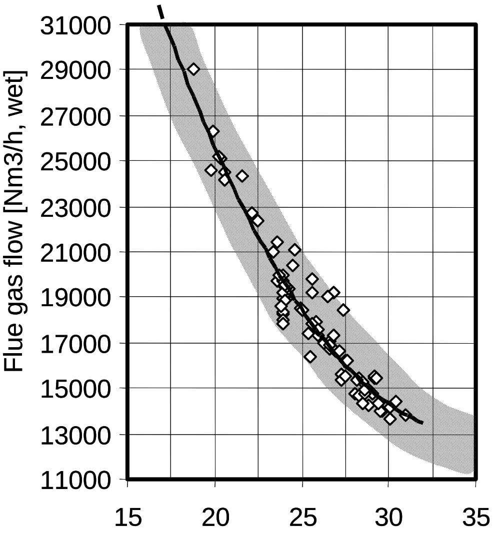


Figure 6. Variation of the flue gas flow at the 30 MW_{th} pilot plant [10]

The operation of the two pilots were good during both air- and oxy-firing testing as conditions could be easily changed and controlled. The pilots operated under various oxy process scenarios and produced flue gas containing more than 90 % CO_2 on a dry basis. A summary of major results is provided below. First operational results from the 30 MW_{th} pilot were already published [5, 6, 7, 8, 9, 10].

1. Flue gas recycle flow

The secondary flue gas recycle flow is required for the combustion temperature control and adjustment of the heat transfer in the boiler between radiation and convection. A reduction of the secondary flue gas flow would decrease the size of the flue gas recycle system as well as the power consumption of the flue gas recycle fan. Subject of testing at the pilot plants was the influence of the flue gas recycle flow on the combustion performance.

At the 30 MW_{th} oxy-combustion pilot plant the flue gas recycle flow was varied within a broad range as shown in *Figure 6*.

The result on the oxygen concentration in the flue gas is shown in *Figure 7*.

2. Oxygen concentration

In oxy-combustion, beside the minimization of conventional emissions like NO_X SO_X, CO and dust, the minimization of oxygen in the flue gas becomes focus of research. The reason is that on one hand oxygen is produced in the ASU with high power consumption and on the other hand the removal of oxygen from the CO_2 product stream in the gas processing unit is energy intensive as well.

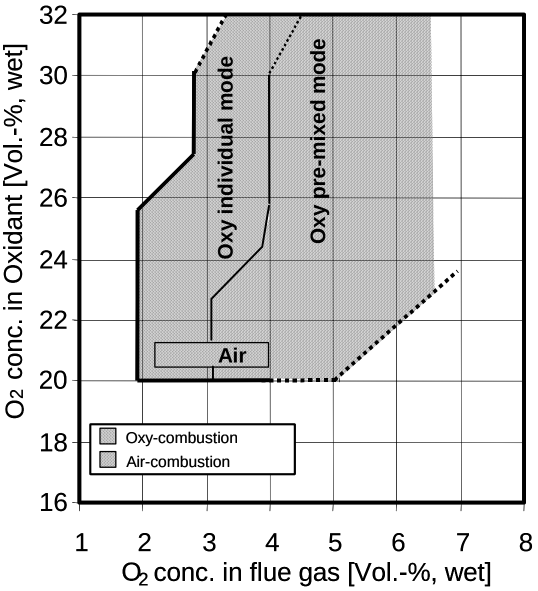


Figure 7: Operational window of the 30 MW_{th} pilot plant [10]

The concentration of oxygen in the flue gas is a quality mark of the combustion process and depends on different factors (e.g. fuel reactivity). The reduction of the oxygen concentration in the flue gas is limited by the fuel burnout especially by the increase of the CO concentration. In conventional combustion processes (air-firing) with pulverized coal, about 15 - 20 % more air than for a stoichiometric combustion needed is required for a good carbon burnout. This results in a O_2 concentration in the flue gas of about 2.8 - 3.5 Vol.-%. The freedom and flexibility of the individual oxygen injection together with the variation of the secondary flue recycle mass flow have been considered in an extensive test program at the different pilot plants in order to explore the limitations of reduction of the overall oxygen consumption and the oxygen concentration in the flue gas. In Figure 7 the operational window with regard to the O_2 concentration in the flue gas dependant on the O_2 concentration in the oxidant (flue gas recycle mass flow) is shown for the 30 MW_{th} oxy-combustion pilot plant. The trend as explored is that with the decrease of the flue gas recycle mass flow the O_2 concentration in the flue gas increases. The borders of the operational window are defined by the emission limits and flame stability.

3. NOX concentration

NO_X control in a conventional coal combustion process is achieved by primary and secondary NO_X control measures. Successful primary NO_X reduction measures are in-furnace air staging and fuel staging (reburning). In brown coal fired units the NO_X emissions levels according to the 13.BImSchV (German emission guidelines) can be kept with primary measures while in a bituminous coal fired unit a selective catalytic

NO_X reduction (SCR) measure is required additionally. In oxy-combustion nitrogen source for NO_X formation is nitrogen from fuel, the thermal NO_X formation process utilizing nitrogen from air can be neglected. This results in a lower NO_X emission freight but due to the missing air nitrogen in the flue gas in a higher NO_X concentration compared to the conventional air combustion process. The described effects on NO_X formation for oxy-combustion have been confirmed with results from pilot plant testing. In-furnace and burner air-staging for NO_X reduction have been intensively tested in pilot scale for air- and oxy-combustion mode and have been considered as a successful NO_X reduction measure for both operation modes. The effect of NO_X concentration increase based on the secondary flue gas recirculation is due to the staging and reburning effects not as significant as for other flue gas components like water, SO_2 etc. NO_X emissions measured during baseline air-firing in the pilot plants were consistent with utility boiler experience. The NO_X emissions from the pilots during oxy-firing were typically less than 50 % of the NO_X levels during air-firing.

4. SOX concentration

The SO_2 concentration in the flue gas is produced by the fuel sulphur combustion. In oxy-combustion the nitrogen from air is kept out of the process and is not diluting the SO_2 flue gas concentration. In case no SO_2 removal device is installed in the secondary flue gas recycle loop the SO_2 concentration will be 4 to 5 times higher in oxy-firing compared to air-firing.

The SO_2 in the flue gas will decrease to concentration levels for SO_2 as experienced in air-firing if the recirculated flue gas is cleaned from SO_2 by a flue gas desulphurization unit before it is injected in the combustion furnace. The SO_3 concentration is dependant on the SO_2 and water concentration and the formation is further enhanced in case a SCR is applied for NO_X reduction. It is likely that the SO_3 level in oxy-combustion increases but it is dependant on the secondary flue recycle take-off location. The result from the pilot plant testing shows slightly increased SO_3 levels for oxy-firing compared to air-firing due to increased SO_2 and water concentration. The net conversion rate of SO_2 to SO_3 appeared to be similar during both air- and oxy-fired tests.

5. CO concentration

Significantly higher levels of CO are experienced on both pilots for the oxy-fired tests in the substoichiometric combustion region of the furnace indicating less heat release. High CO concentrations in substoichiometric regions are expected and confirmed by probe sampling measurements during oxy-firing due to gasification reactions with the higher CO_2 and water contents in the gas stream. After over-fired oxidant addition, the CO concentrations for both air- and oxy-fired tests rapidly decrease to similar levels and reach low ppm levels by the furnace outlet for both air- and oxy-fired tests.

6. Heat Flux Profiles

Furnace heat absorption and furnace heat flux profiles during oxy-firing could be controlled to similar levels as measured during air-firing. Furnace heat transfer could be changed during oxy tests by varying flue gas recycle rate, oxygen injection location and oxygen concentrations in the oxidant streams.

One focus of the testing at the 15 MW$_{th}$ BSF was the evaluation of differences in combustion and heat release rates during oxy-combustion. Furnace heat flux profiles based on total incident heat flux probe measurements averaged from several locations at each plane at similar thermal input and combustion stoichiometric are shown in *Figure 8*. Also shown in Figure 8 are furnace temperature profiles based on averaged gas temperature measurements for planes at different elevations.

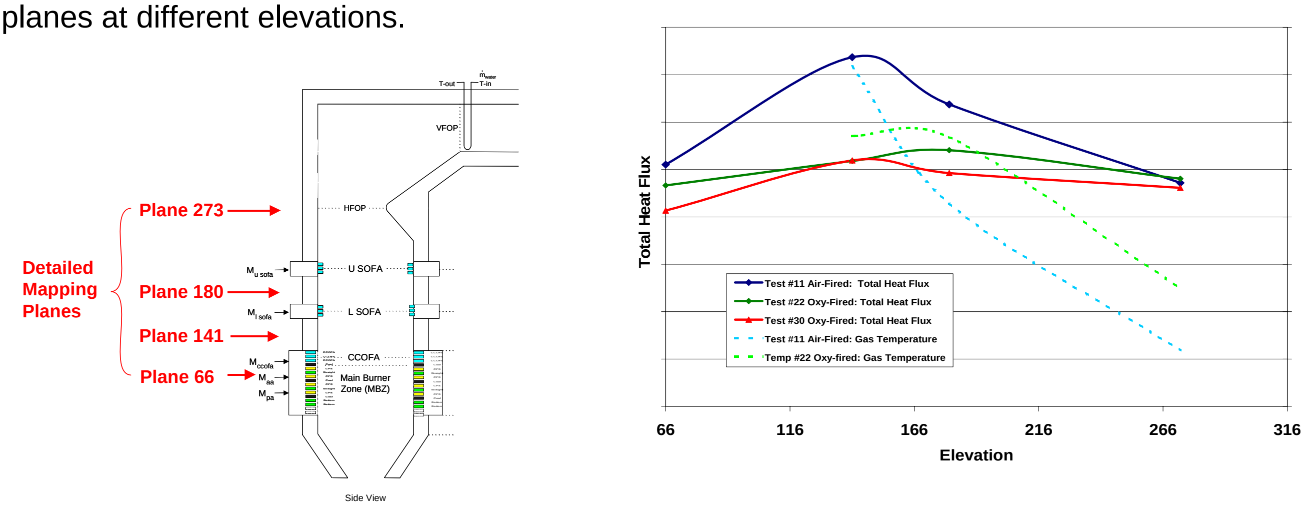


Figure 8: Main focus of the investigation for the oxy-combustion boiler

Peak temperatures and peak heat fluxes were higher during the air-fired test compared to the oxy-fired tests. However, it must be noted that the behavior during the oxy-fired tests plotted above is dependent on the specific test conditions selected and can be changed by varying conditions.

7. Ash deposition and ash burnout

Ash deposition on waterwall and convection heating surfaces was generally similar in composition and physical characteristics during both oxy and air-firing tests. The analytical results of ash samples collected in the furnace hopper and flue gas filter in air- and oxy mode were consistent with utility boiler experience.

8. Dynamic processes

The connection of the other key components of the oxy-chain including air separation unit (ASU), air quality control systems (AQCS), condenser and CO_2 purification and liquefaction unit (GPU) to the boiler was successfully and very smoothly achieved at the Vattenfall's 30 MW_{th} oxy-combustion pilot plant. Only minor adjustments of the planned control structure had to be made.

In order to learn as much as possible for the operation of future large-scale plants all standard procedures such as venting, start-up and shutdown as well as load changes were automated, in order to reach the same degree of automation as a commercial plant.

Typical periods of time for standard procedures:

- Venting of boiler and flue gas paths: approx. 20 minutes
- Start of fire up to full load: approx. 45 minutes
- Switch from air to oxy-combustion mode: approx. 20 - 30 minutes

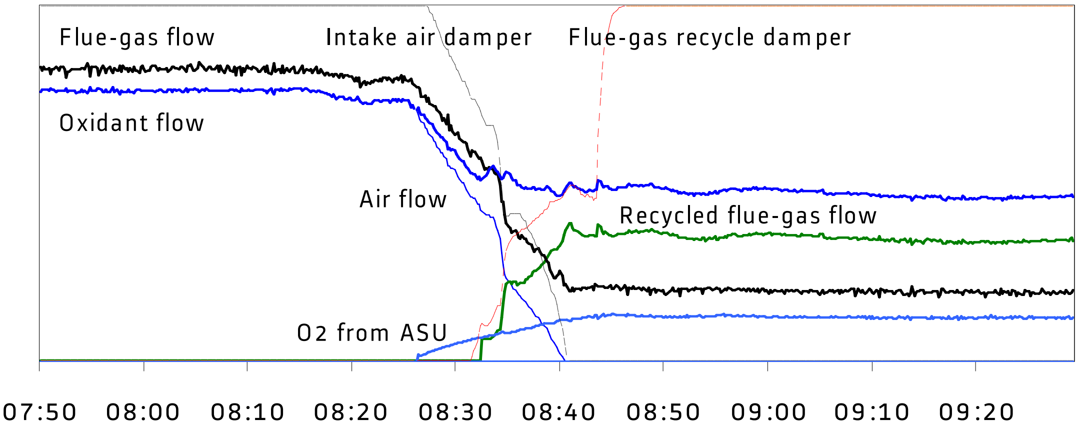


Figure 9: Switchover procedure 30 MWth oxy pilot – air to oxy-combustion (volume flows)

Figure 9 shows the transition from air to oxy-combustion mode. For the switchover process, it can be acknowledge that ~20 minutes only are required from the start of the closure of the intake air damper until the complete opening of the flue gas recycle damper. As expected, the flue gas concentrations change slower due to the flue gas recirculation. After a parameter modification, steady-state conditions were achieved within 30 to 45 minutes.

9. CFD model development and validation

On both pilots detailed in-furnace measurements were performed in air- and oxy-firing conditions in order to collect data for CFD modeling. The comparisons between model predictions and measurements are being used to evaluate and refine CFD code submodels to improve and validate oxy-combustion predictions.

As an example, *Figure 10* shows CFD predictions of CO concentrations for air- and oxy-firing at a centerline slice of the 15 MW_{th} pilot (BSF). At these test conditions significantly higher levels of CO are shown for the oxy-fired test in the substoichiometric combustion region of the furnace indicating less heat release. These CFD predictions are consistent with the probe sample measurements.

After over-fired oxidant addition, the CO concentrations for both air- and oxy-fired tests rapidly decrease to similar levels and reach low ppm levels by the furnace outlet plane for both air- and oxy-fired tests.

More detailed comparisons between CFD predictions and actual probe measurements are in progress using updated simulations to match the actual measured flow streams and boundary conditions during testing.

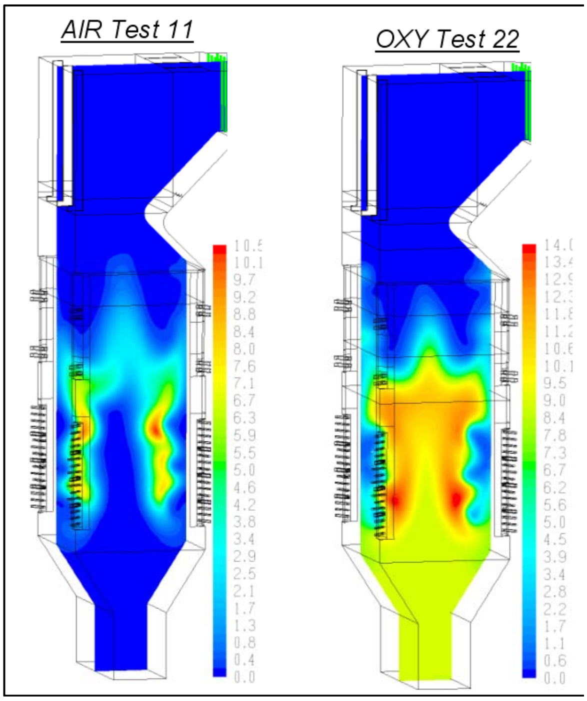


Figure 10: CO distribution predicted for air- and oxy-fired test conditions

The results from these pilot plants and supporting investigations offer a broad knowledge base to Alstom for the design, construction and operation of an oxy-combustion demonstration power plant in the capacity class of 200 – 300 MW_e as the last intermediate step towards a commercial power plant.

E. Gas Processing Unit – GPU

One of the other key subsystems under investigation within the oxy-combustion technology is the Gas Processing Unit (“GPU” positioned at the interface between the oxy power plant and the CO_2 transport and storage interface).

One advantage of oxy power plant is its ability to deliver several qualities of CO_2 product at GPU outlet, from very stringent specifications : >99% for applications such as Enhanced Oil Recovery down to more relaxed specifications typically 95% or lower in some cases for storage in saline aquifers when it is possible depending on site and transport and storage configuration and characteristics.

As presented in figure 11, the Gas Processing Unit can be divided into the following main sub-systems :

- Flue Gas Condenser
- Flue Gas Compression
- Conditioning and Drying
- Regeneration Gas System
- Chilling and CO2 Separation
- Off-gas System
- CO2 Recompression

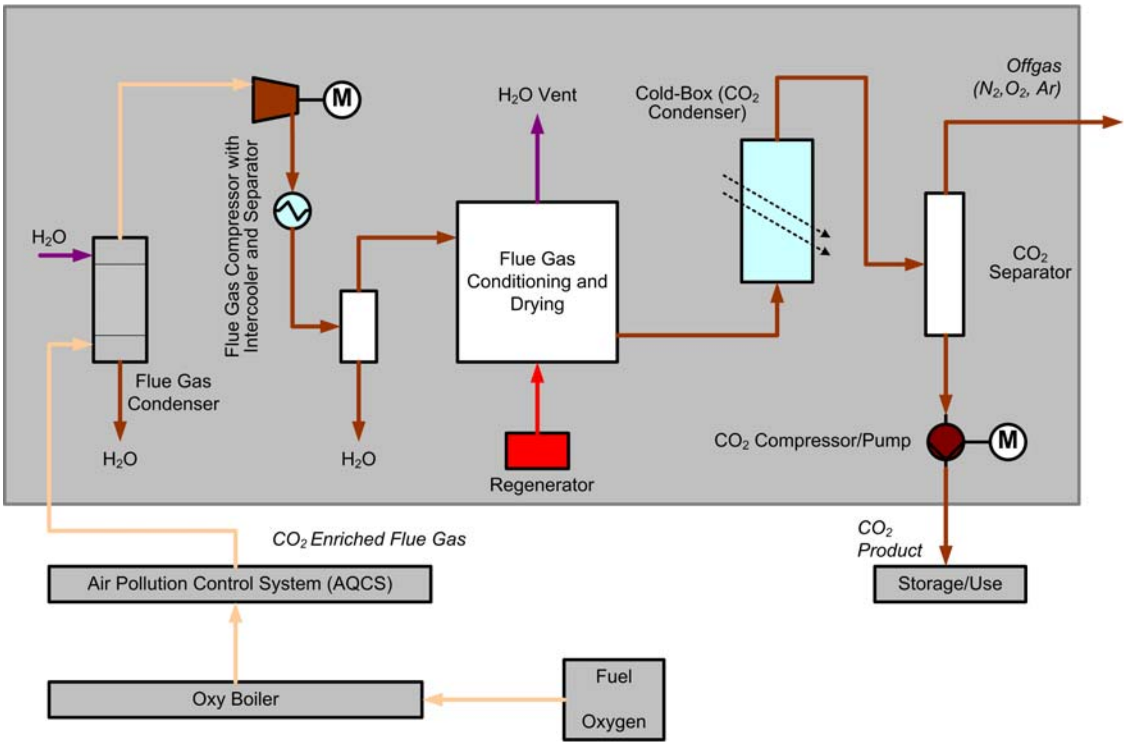


Figure 11: Overview of a gas processing unit for an oxy-combustion power plant

One objective of the development of the GPU is to minimize the energy consumption.

Alstom has in house expertise for similar types of systems for various applications at one of its facilities in Germany. Alstom acquired the Wiesbaden engineering office of the former Lummus Global, a leading provider of technology for the hydrocarbon processing industry, in Germany. The unit, renamed Alstom Carbon Capture GmbH, is now integrated into Alstom’s CO2 Capture Systems activity.

Alstom Carbon Capture GmbH has extensive experience in numerous fields of chemical processing applications, especially for the oil and gas, petrochemical and Chemical Processing Industries. For the Gas Processing Unit, Alstom has developed a comprehensive development program to support the global oxy-combustion program, including optimization of its interfaces with other power plant subsystems and global evaluation of trade-offs and integration with the other components of the oxy-plant.

Within this development program, Alstom is currently installing Gas Processing Unit test pilots in its Alstom promises of Växjö in Sweden. The first phase of these GPU pilot tests is expected to start end of this year will be oriented to the compression part, then a second phase will test the purification part of the GPU.

The test program will start with synthetic flue gas and is expected to be followed by actual oxy-combustion flue-gases. The configuration of these GPU pilots in containers (see figure 12 showing the compression container) will allow mobility for testing in different location and under different conditions.

The main goal of the GPU pilot tests are to (i) validate the simulation data (ii) confirm the assumptions in view of the design of gas processing units for large oxy projects (material selection, purification stage assumptions and targets in terms of pollutants removal within the GPU, etc).

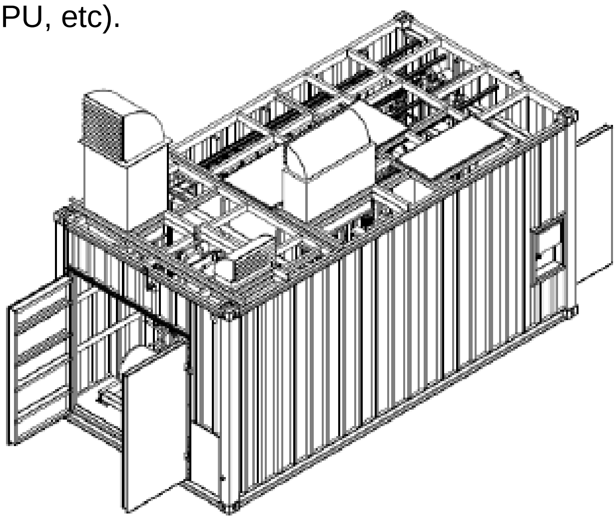


Figure 12 : GPU compression pilot - Växjö, Sweden

F. An integrated approach to oxy-combustion

As mentioned earlier an integrated approach is key to design of an optimized oxy-combustion power plant.

Several types of integration can be envisaged : process, thermal, operation and layout (see below figure 13). Alstom's expertise in thermal power plants design combined with its unique experience of the flue gas chain components offers niche expertise in the development of Oxy-Combustion. The optimization work that needs to occur very early during project development and definition phase.

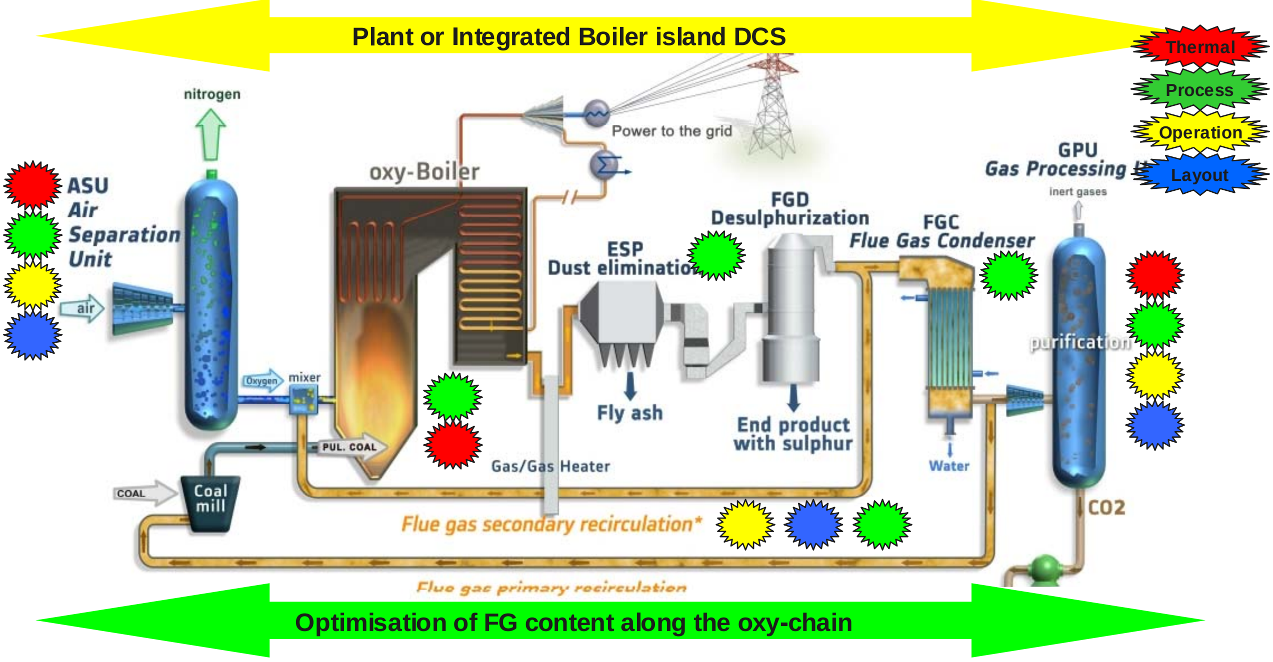


Figure 13 : oxy-chain design requires assessment of the multiple integration possibilities

Contrary to the conventional Post-Combustion systems using solvents, Oxy-Combustion does not require regeneration heat and therefore, no significant modifications to the steam turbine or turbine island are required. As per Figure 8, Oxy-Value Chain and its key components are located along the flue gas chain.

For the subsystems themselves, the first level of integration should be incorporated during basic design and equipment specification phase.

The Air Separation Unit, which is the major auxiliary in terms of energy consumption and space allocation to be a primary focus. Currently, suppliers develop very large ASUs with optimized energy consumption specifically for the oxy-combustion application. Heat loss of the ASU can be recovered within the cycle (exact location depending on cycle conditions and site specificities). Utilities for the ASU (cooling, electric power, etc) to be integrated with other power plant auxiliaries. In addition, the

ASU will be specified to feed the oxy-boiler and to follow its operation. Therefore, depending on the specific project requirement, the ASU and its auxiliaries (storage tanks, start-up times, etc) should be designed to follow the boiler load changes and its specific operation modes.

Lessons learnt from the pilot plants and especially the integrated pilot plants where the Oxy-boiler is connected to an ASU and downstream AQCS and GPU (such as Schwarze Pumpe) can be used for the AQCS and oxy-boiler. The boiler and AQCS be designed to minimize air-leakage which in turn will benefit the GPU design and cost. Depending on the fuel sulfur content and other contaminants, the location of the flue gas re-circulation to be assessed: pros and cons of larger desulphurization versus sulfuric components levels or other contaminants in the re-circulated gas to be designed specific to a project. The design will also depend on the different operating modes chosen for the power plant (dual-mode or oxy-operation only).

As per the ASU, the GPU is one of the major subsystems of the oxy-chain and has an important impact on the cost and energy penalty. The cost, consumption and design is highly dependent on the CO_2 product specification at the outlet of the GPU as well as on the design of upstream equipment. The GPU will be designed to optimize the auxiliary consumption and cost whilst also taking into account the potential trade-offs along the oxy-chain (CO_2/O_2 content versus global evaluation of flue-gas composition for each step, capture rate, operation modes and conditions, etc). Similar integration as for ASU can be envisioned (heat integration, process, layout and operation).

G. Conclusion

Based upon the development efforts for Oxy-Combustion process and the results from the pilots, Alstom strongly believes that oxy-combustion will play a key role in forthcoming CCS deployment. The advantages of this technology are summarized below :

- Oxy-combustion is a sound CO_2 capture solution, derived from existing processes and requiring adaptation to this new application;
- Most of these subsystems are based upon proven technology and the field pilot projects demonstrated smooth operation and positive results;
- The various types of boilers and firing configurations are adaptable to oxy-combustion;
- No significant modifications to the turbine island are required;
- Type and quantity of contaminant emissions profile will be unchanged**;**
- Oxy-combustion can address the existing fleet, supported by Alstom expertise in power plant retrofit;

- High efficiency and very large size units for the commercial phase will be possible and, in combination with an integrated approach, will be key advantages in the optimization of performance and global cost of electricity.

To attain the commercial phase, oxy-combustion should however pass successfully the demonstration phase. Unfortunately the number of demonstration projects currently under development in oxy-combustion is low, despite the numbers of advantages described above. In order to pass successfully the demonstration phase, projects based on boiler retrofit solution could also be considered to limit the project costs, but still allowing the validation of the necessary criterion.

An integrated approach during the design phase of the oxy-chain will also be a key advantage to optimize the resulting cost of electricity over plant life by balancing performance-versus-investment.

In addition, oxy-combustion will open the door to a second generation of oxy-products that is expected to constitute a breakthrough technology in terms of performance : chemical looping combustion. The development of this technology, expected to be available in 15+ years from now, will benefit from the oxy-combustion technical development as several subsystems will be similar, such as AQCS and Gas processing Unit.

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REFERENCES

1. P. Paelinck, J.F. Léandri, B. Prodhomme, F. Kluger, J. Black, "Alstom CO2 Capture technology development – update on Carbon Capture technology and Pilot operation", powergen Europe, 2010;
2. F. Kluger, S. Darling, N.Y. Nsakala, JF. Léandri, "Oxy-Combustion: A Sound and Near Term Technology to CO2 Emissions Reduction – Development and Next Steps", powergen international 2009;
3. F. Kluger; P. Moenckert, G-N. Stamatelopoulos, A. Levasseur, "Alstom's Oxy-Combustion Technology Development – Update on Pilot Plants Operation"- 35th International Technical Conference on Clean Coal & Fuel Systems, 2010
4. Kluger, F., Lysk, S., Altmann, H., Krohmer, B., Stamatelopoulos, G.-N.: 30 MWth Oxyfuel Pilotanlage - Untersuchungsschwerpunkte und Auslegung des Dampferzeugers, 38. Kraftwerkstechnisches Kolloquium 2006, Dresden, Germany
5. Strömberg, L., Lindgren, G., Jacoby, J., Giering, R., Anheden, M., Burchhardt, U., Altmann, H., Kluger, F., Stamatelopoulos, G.-N., First test results from Vattenfall's 30 MWth Oxyfuel Pilot Plant in Schwarze Pumpe, 34th International Technical Conference on Clean Coal & Fuel Systems, Florida, USA, 2009
6. Paelinck, P., Altmann, H., Overview CCS technologies / Results from oxfuel pilot plant Schwarze Pumpe, VGB Congress Power Plants 2009, Lyon, France, 2009
7. Kluger, F., Mönckert, P. Krohmer, B., Stamatelopoulos, G.-N., Jacoby, J., Burchhardt, U., Oxyfuel Pulverized Coal Steam Generator Development - 30 MWth Pilot Steam Generator Commissioning and Testing, 1st Oxyfuel Combustion Conference, Cottbus, Germany, 2009
8. Kluger, F., Krohmer, B., Mönckert, P., Stamatelopoulos, G.-N., Entwicklung der Oxyfuel-Technologie – Pilotprojekte mit Alstom Beteiligung, 41. Kraftwerkstechnisches Kolloquium 2009, Dresden, Germany, 2009
9. Wild, T., Lysk, S., Kluger, F., Bischoff, H., Besonderheiten von Feuerungen in Oxyfuel-Dampferzeugern und Auswirkungen auf Auslegung und Betrieb, VGB Fachtagung - Brennstofftechnik & Feuerungen, Kassel, Germany, 2010
10. Darling S., Prodhomme B, Kluger F. Heinz G. Stallmann O., Casier F., Coal-gen, USA, 2010.