



# Advanced Oxyfuel Combustion Leading to Zero Emission Power Generation

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## Advanced Oxyfuel Combustion Leading to Zero Emission Power Generation

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### ABSTRACT

Advanced power plant designs will play a major role in the reduction of CO<sub>2</sub> emissions from fossil fuel-based power generation. As world leaders discuss ways to minimize climate change due to greenhouse gas emissions, Foster Wheeler is developing power plant designs of PC and CFB boilers that reduce carbon-dioxide emissions through oxyfuel combustion where the air, as oxidant, is replaced by a mixture of nearly pure oxygen from an air separation unit (ASU) and recycled flue gas. As a result, the flue gas from the combustion process is free of nitrogen and contains mostly CO<sub>2</sub> and water. The concentrated gases enhance reaction kinetics and mass transfer, and potentially suppress the formation of contaminants and pollutants. Flue-gas recirculation is incorporated in the design to control furnace temperature and to optimize boiler operation. This gas recirculation helps to reduce pollutant emissions by enhancing re-burning and re-capturing in the boiler. In the present example, simulation results indicate that the NO<sub>x</sub> from the recycled gas is consumed in the fuel rich combustion zone, and that sulfur capture is enhanced either in-bed or in the downstream scrubber.

True zero-emissions power generation can be achieved under oxyfuel combustion if all of the product gases are recirculated to the boiler, and undergo re-burn and re-capture within the closed-loop system. A new process has been investigated by Foster Wheeler, where all vent gas streams from the downstream CO<sub>2</sub> purification unit (CPU) have been designed to flow back to the boiler. To avoid accumulation of nitrogen and argon (N<sub>2</sub>+Ar), a pressure swing adsorption (PSA) process was applied to the vent gas before recirculation, where purified N<sub>2</sub>+Ar passes through the PSA, and the other gases, including part of the N<sub>2</sub>+Ar regenerated from the adsorption process, are recirculated back to boiler.

The beauty of this zero-emissions process is in that it achieves 100% CO<sub>2</sub> removal without increasing the ASU duty, and it performs a simple emissions control to reach zero emissions of atmospheric and condensate pollutants through a closed-loop gas recirculation system. NO<sub>x</sub> control, under this process, does not require any conventional deNO<sub>x</sub> processes, such as SCR or SNCR, and it potentially relaxes the requirements for combustion staging. The results of this investigation have demonstrated that the incorporation of a closed-loop zero emissions system into an oxyfuel combustion process will result in a lower penalty of CO<sub>2</sub> removal. This approach is applicable for both Greenfield and retrofit applications.

## INTRODUCTION

With the significant abundance of coal for power generation, solutions need to be developed for control of pollutant emissions including the greenhouse gas  $\text{CO}_2$ . In the short term, power plant efficiency improvement can reduce  $\text{CO}_2$  emissions. However, carbon capture and sequestration (CCS) will provide a long term solution for fossil fuel fired power generation, where the oxyfuel combustion represents a favorable CCS method among wide variety of potential  $\text{CO}_2$  capture technologies. Foster Wheeler is developing power plants, with Flexi-Burn technology for both PC and CFB boilers, as its CCS solution to address  $\text{CO}_2$  emissions based on both bench and pilot scale experimental tests (PC and CFB, as well as material testing) and through system level integration and evaluation. One of goals for the improvement of oxyfuel combustion is to combine  $\text{CO}_2$  capture and sequestration with other emission controls to form power generation with zero emissions of atmospheric and condensate pollutants and to reduce costs. It is a challenge but also an opportunity for power industry.

Oxyfuel combustion has made significant progress through system level integration studies and pilot scale tests (Ref. 6). Figure 1 shows a simplified process flow diagram of an oxyfuel combustion power plant (Ref. 1), which consists of an air separation unit (ASU) for oxygen supply, a power plant with PC or CFB boiler under oxy-firing with gas recirculation for temperature control, and a  $\text{CO}_2$  compression and purification unit (CPU) for meeting the requirement and specification of  $\text{CO}_2$  transport and sequestration. Hot and/or cold gas recirculation is required for the right boiler operation. For the PC boiler, the  $\text{SO}_x$  in the primary recirculation gas (PG) to mill needs to be cleaned to avoid acid gas condensation. The  $\text{H}_2\text{O}$  in PG also needs to be reduced for proper fuel drying in the mill. Hot gas circulation (before fluegas clean up) to reduce low grade heat discharge and recovery is also possible as shown in Figure 1 (Ref. 8). It is noted that the wet-FGD does not remove heat, instead, it converts gas sensible heat to latent heat by water evaporation. This water vapor needs to be condensed out downstream of FGD, which essentially shifts the gas cooling to a cooler at a very low LMTD without any heat recovery. To avoid this evaporation-condensation, wet-end heat exchangers have been applied before and inside the FGD to recover the heat for improved system efficiency and more efficient cooling of the gas to reduce the cooling water requirement.

In oxyfuel combustion,  $\text{CO}_2$  is produced and concentrated by fuel combustion with oxygen in a

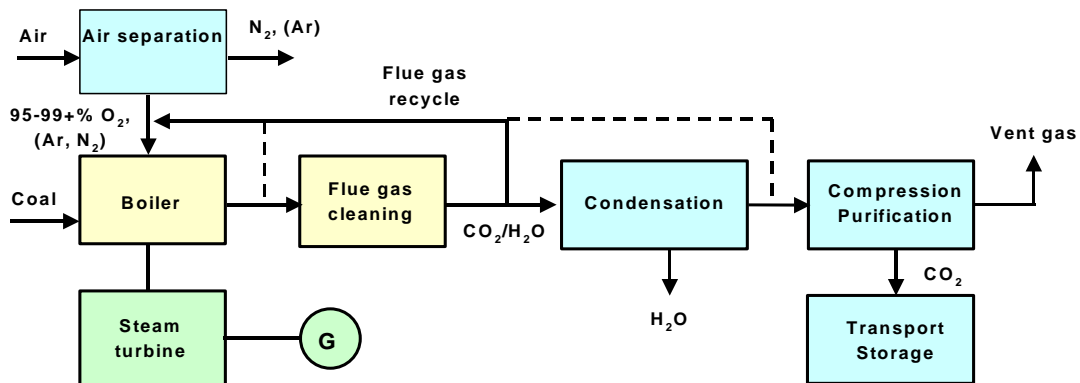


Figure 1 Block flow diagram of oxyfuel combustion for  $\text{CO}_2$  removal

N<sub>2</sub>-free environment. Because of air separation and energy stored in compressed CO<sub>2</sub> there are certain penalties associated with CO<sub>2</sub> capture and sequestration. It has been noted that in spite of whether CO<sub>2</sub> is captured or not, the penalty exists just for oxyfuel combustion itself due to the requirement of pure oxygen from ASU for combustion. Thus for CO<sub>2</sub> removal, considering more than half of penalty (ASU+CPU) comes from ASU, it is more economic to capture as much CO<sub>2</sub> as possible

Inert gases in the CO<sub>2</sub> stream to the CPU are vented during CO<sub>2</sub> purification and compression. Because of the partial pressure of CO<sub>2</sub>, a certain amount of CO<sub>2</sub> will be vented with inert gases together. This limits the efficiency of CO<sub>2</sub> recovery and increases the CO<sub>2</sub> removal penalty. As a result, for better CO<sub>2</sub> removal efficiency, it is desirable to increase fluegas CO<sub>2</sub> concentration, which can be done by reducing the concentration of the inert gases in CO<sub>2</sub> stream, such as by raising oxygen purity from ASU, by sealing boiler to avoid air ingress, and by firing with low excess oxygen, all of which incur extra cost. But even with substantial efforts to increase CO<sub>2</sub> purity, the inert gases in the CO<sub>2</sub> stream cannot be fully avoided, and a near 100% CO<sub>2</sub> removal is still not reachable for such a once-through CO<sub>2</sub> capture process.

An alternative way to enhance CO<sub>2</sub> capture is to reduce or capture CO<sub>2</sub> from the vent gas. In considering the costs of upgrading the ASU and CPU, further investment for recovery of CO<sub>2</sub> from the vent gas becomes economically favorable. Any method which can separate CO<sub>2</sub> from the vent gas or separate inert gas from CO<sub>2</sub> can be applied to recover extra CO<sub>2</sub> and so to improve CO<sub>2</sub> removal efficiency. Such methods include membrane method by Air Products to recover the extra CO<sub>2</sub> and O<sub>2</sub> from vent gas to boiler (Ref. 2), and VPSA method by Praxair to recover the extra CO<sub>2</sub> from the vent gas and recycle it inside the CPU. Both of these enhance CO<sub>2</sub> recovery efficiency and reduce the penalty of CO<sub>2</sub> removal.

## ZERO-EMISSION DESCRIPTION

A new multi-emissions control process producing zero emissions was originally developed by Foster Wheeler in 2007 and has been steadily improved over the last three years. Note that in this paper the term, “emissions”, refers specifically to all gaseous and liquid pollutants (SO<sub>x</sub>, NO<sub>x</sub>, CO, CO<sub>2</sub>, VOC, HCl, Hg etc.). This new zero emission process employs vent gas treatment to enhance CO<sub>2</sub> capture, where a PSA type sorbent bed is applied to adsorb CO<sub>2</sub> and the other gases at vent gas condition, which is very similar to the hydrogen purification method in hydrogen production through reforming. The un-adsorbed or less adsorbed gases, mainly purified Ar, N<sub>2</sub> and O<sub>2</sub> are purged, or forwarded to ASU (if oxygen concentration is high enough to save ASU power and if Ar concentration is low enough to avoid accumulation in system). The PSA adsorbed gases with all emission components including CO<sub>2</sub> are released by pressure reduction (flashing) and, after coolant recovery, forwarded to boiler as part of recirculation gases, where any emission gases will flow through the boiler and undergo re-burn and re-capture processes during gas recirculation.

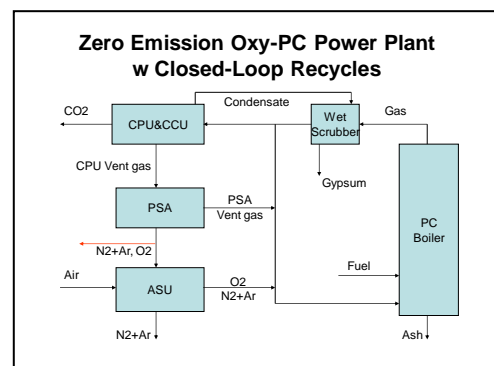


Figure 2 - Zero-emission oxyfuel power plant

During research, it has been found (Ref. 3) that recirculating flue gas through the boiler induces re-burn and re-capture of many pollutants. For example, the NO<sub>x</sub> in recirculation gas can be well destroyed (nearly 100%) in the high temperature zone under fuel rich conditions, and about 60-70% destroyed under fuel lean conditions. Furthermore, SO<sub>3</sub> can be reversely converted back to SO<sub>2</sub> in the high temperature zone. CO and VOC in the recirculation gas are primarily burned out in the high temperature zone and will not cause any accumulation in circulation. This re-burning brings another advantage that the boiler can be operated at low excess oxygen despite the CO level as long as the UBC (unburned carbon) is not significantly increased. These re-burn effects greatly reduce the concentration of emission components in gas. The re-capture is another function induced by gas recirculation, where gases pass repetitively through emission control devices such as for SO<sub>x</sub> capture. The vent gas, flowing through the boiler, become part of recirculation gas and undergoes both re-burn and re-capture. Without the re-burn and re-capture, gas components reach 4-5 times higher due to N<sub>2</sub> dilution free combustion.

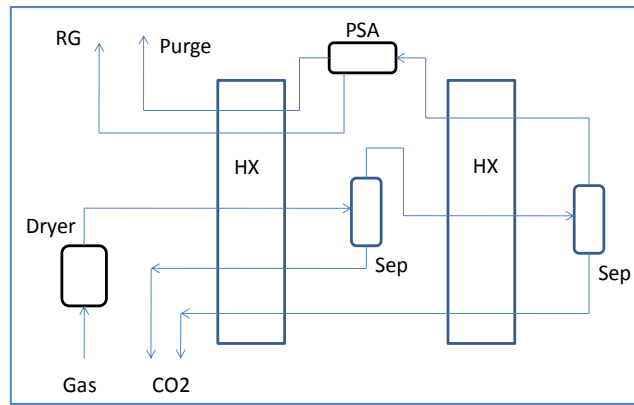
To avoid ice formation during CO<sub>2</sub> condensation at low temperature, the gas moisture in the CO<sub>2</sub> stream has to be removed before cold box, which is done by a sorbent bed before cooling. It has been noted that part of gases, including SO<sub>x</sub> and NO<sub>x</sub>, are also possibly adsorbed (Ref. 4) by the sorbent bed during gas drying, where the extent of adsorptions depend upon the sorbent applied. Based on the present zero emission approach, the regenerated gas stream from this sorbent bed is also forwarded to the boiler-island and treated as part of recirculation gas.

The natural acidic condensate drained from the CPU is directly forwarded back to the scrubber in boiler-island as makeup water without additional treatment, where those acid components in condensate will be captured and neutralized (Figure 2).

This configuration is a system with closed-loops to emission components, producing only purified (N<sub>2</sub>+Ar+O<sub>2</sub>) gas, solid related gypsum (PC) or solid drain (CFB), and purified CO<sub>2</sub>. This process does not require a sharp cut or separation by PSA and can reach 100% CO<sub>2</sub> removal. It does not require any deNO<sub>x</sub> process as NO<sub>x</sub> can be adsorbed with CO<sub>2</sub> together by PSA. For the same reason, the emissions control of VOC, CO and other pollutants are complete if they can be adsorbed by PSA and recirculated back to boiler after regeneration.

The key point of this zero-emission approach is the vent gas recirculation to boiler-island to form a closed-loop system of the emission components, where any separation methods to separate and re-circulate emission components to boiler-island are applicable. The PSA method applied here is just an example.

The key for success to this zero-emission approach is a sorbent bed to purify (N<sub>2</sub>+Ar) and to send all emission gases to boiler-island. Recently, CO<sub>2</sub> adsorption has become a hot topic for CO<sub>2</sub> removal aiming at reducing energy penalty from regeneration and lowering capital costs (Ref. 7). Different sorbents such as active carbon, molecular sieve, and zeolite (Ref. 5), have been tested. Research is required to find a good sorbent which selectively adsorbs or absorbs CO<sub>2</sub> from fluegas while possessing a high capacity in loading in term of lb-CO<sub>2</sub>/lb-sorbent to lower sorbent circulation rate and the extra heat requirement for regeneration. The purity of regenerated CO<sub>2</sub> from adsorption relies highly on the CO<sub>2</sub> selectivity during adsorptions. The relative CO<sub>2</sub> selectivity therefore becomes important for sorbent evaluation and development.



**Figure 3 - Block diagram of CO<sub>2</sub> purification by condensation**

The present zero-emission approach uses PSA for vent gas treatment, which functions as a guarding device to prevent any emission components to be vented. Since the regenerated gas from the vent gas treatment will be forwarded to boiler-island as part of recirculation gas for emission control, the PSA used in the zero-emission process prefers, but does not require, a high selectivity of CO<sub>2</sub> from the other gases. Instead, it just requires a good selectivity between (Ar+N<sub>2</sub>) and the other gases to reduce PSA size.

The beauty of vent gas treatment by PSA is that it not only increases CO<sub>2</sub> recovery efficiency to 100% with reduced cost per CO<sub>2</sub> removal, but also forms closed-loops for the emission components to reach true zero emissions. This zero-emission approach also allows relaxation of boiler operational parameters, such as low excess oxygen in spite of potentially high CO concentration. It could be expected that the zero emission system can tolerate the ingress of air into CO<sub>2</sub> stream. For the same reason, it can also tolerate a low oxygen purity, which is a big advantage to reduce ASU auxiliary power and cost, as well as to promote application of advanced ASU methods with low oxygen purity.

## MODELING

This zero-emission concept is applicable for both PC and CFB power plants. A nominal 450 MWe oxy-PC boiler was applied for analysis. The furnace performance is simulated by Foster Wheeler 3-D CFD furnace models, which include calculations for SO<sub>x</sub>, NO<sub>x</sub> and CO as well as UBC under different excess oxygen levels and gas recirculation rates. The effects of the re-burn and re-capture from gas recirculation are included in the modeling. The over-fired air (OFA) has been turned off due to application of the zero-emission where the furnace itself functions for NO<sub>x</sub> reduction. The system heat and material balances are simulated by Aspen Plus<sup>®</sup> commercial software. A fixed total gas recirculation rate was maintained in the model for the parametric study.

There are many different CPU configurations presented in the literature. For the parametric study of the potential gains of the zero-emission process, a common CO<sub>2</sub> purification process with two-stage CO<sub>2</sub> condensation was applied (Figure 3). To recover as much energy as possible, both streams exiting from the PSA pass through the cold box for coolant recovery. The purified CO<sub>2</sub> streams are then compressed to the end pressure of 2000 psia. Regenerated gases from PSA and dryer are treated as part of recirculation gases. The flashing of the purified vent gas (N<sub>2</sub>+Ar+O<sub>2</sub>)

for cooling can also be done by gas expansion at low temperature to recover power directly when this vent gas flow is significant.

There is no test data available for PSA operated at vent gas condition. It has been assumed that the relative selectivity at room temperature can be applied to low temperature, and the O<sub>2</sub>, N<sub>2</sub> and Ar have the same relative selectivity as compared with the other gases for a given sorbent. The PSA adsorption performance, or recovery of (N<sub>2</sub>+Ar+O<sub>2</sub>), can then be obtained by integration of relative selectivity along sorbent bed, where the total recovery of (N<sub>2</sub>+O<sub>2</sub>+Ar) is affected by the operating pressure and feed composition.

It has been demonstrated that both NO<sub>x</sub> and SO<sub>x</sub> can potentially form acids under high pressure and low temperature during CO<sub>2</sub> compression. In the zero-emission process, the acidic CPU condensate forms a closed-loop for liquid emission components, where all condensates from the CPU are recycled back to the boiler scrubber. All emission components in liquid will be captured and removed by the scrubber. The condensate, mainly water, is used as makeup water for scrubber operation.

## RESULTS

A parametric study was conducted to evaluate the effect of PSA selectivity, air ingress, and furnace excess oxygen on the zero-emission performance in terms of specific power and emissions. The CO<sub>2</sub> capture power penalty depends upon the power plant heat integration, the ASU and CPU configuration and design, and raw CO<sub>2</sub> purity to CPU. For simplicity, a relative specific power of (ASU+CPU) per tonne of CO<sub>2</sub> removed is calculated. Table 1 shows different cases for CO<sub>2</sub> purification, with and without the use of the zero-emission process, where the base case power has been normalized to 100% for comparison.

As can be seen, a 100% efficiency CO<sub>2</sub> removal was obtained when the zero-emission is applied regardless of the level of air ingress. For 5% air ingress, the zero-emission boosts the CO<sub>2</sub> capture efficiency from 91.1% (case-A) to 100% (case-C), which corresponds to about 10% extra CO<sub>2</sub> captured. It is not surprising that for this 10% extra CO<sub>2</sub> capture that there is a 10% change in CPU auxiliary power, but there is no change in ASU auxiliary power. As a result, the specific power is reduced by 4.7% when the zero-emission process is applied. If the boiler is sealed to reduce air ingress from 5% to 2%, the specific power gain of the zero-emission is 1.7% (case-B to case-D). Adding together reducing the ingress from 5% to 2% and switching to zero emission, the total specific power gain is 10% (case-A to case-D). But most importantly zero emissions are obtained in spite of air ingress.

The effect of PSA operation pressure on the performance of CO<sub>2</sub> removal was evaluated as shown by Table 1, where in case-E the PSA has a 93% recovery of (N<sub>2</sub>+O<sub>2</sub>+Ar) operated at 120 psia and case-D has a 89% recovery at 250 psia. In considering the pressure effect on gas volumetric flow to PSA and driving force (partial pressure) for gas adsorption in PSA, the PSA size will be affected by the pressure squared. Therefore a high PSA operating pressure is preferable. There is no effect of PSA pressure on CO<sub>2</sub> removal, and a very minor effect on specific power (by 0.1%, case-D to case-E) because the gas flow to the PSA changes by only 4%

while PSA recovery changes by 4% points. From all of these facts, the vent gas flashing before the PSA needs to be minimized to hold a high PSA operating pressure.

**Table 1 - Case summary for with and without zero-emission approach**

Case		Oxy-A	Oxy-B	Oxy-C	Oxy-D	Oxy-E	Oxy-F
Zero-Emission		no	no	yes	yes	yes	yes
PSA Recovery	%			89	89	93	89
Air Ingress	%	5	2	5	2	2	5
Fluegas O2	%v	3	3	3	3	3	1
CO2 removal	%	91.1	96.3	100	100	100	100
ASU power	%	100	102.0	100.0	102.0	101.8	97.2
CPU power	%	100	91.1	109.8	95.5	95.0	103.8
Specific power	%	100	91.8	95.3	90.1	90.1	91.7
<b>Purged Vent Gas</b>							
O2	%	12	17	16	21	22	22
N2	%	57	46	74	60	60	60
Ar	%	8	14	10	19	19	18
CO2	%	23	23	0	0	0	0
CO	%	0.1	0.2	0	0	0	0
NOx	%	0.2	0.3	0	0	0	0
<b>Recycled Vent Gas</b>							
O2	%			4.2	5.8	4.2	4.2
N2	%			20	16.2	11.4	11.3
Ar	%			2.7	5	3.5	3.5
CO2	%			72.2	71.6	79.5	79.4
CO	%			0.3	0.6	0.7	0.7
NOx	%			0.5	0.8	0.7	0.9

There is no difference in purity of the outlet CO<sub>2</sub> stream of the different cases. The purity of CO<sub>2</sub> is mainly determined by gas solubility in liquid CO<sub>2</sub> which is fixed by the phase equilibrium corresponding to the operating pressure before flashing. The CO<sub>2</sub> purity can be increased by lowering the operating pressure, but this will reduce the once-through CO<sub>2</sub> recovery. It is better to raise CO<sub>2</sub> purity by adding a distillation column to further purify the CO<sub>2</sub> stream. However, on a relative basis, the comparison of the zero-emission to the conventional oxyfuel system will not be affected by the addition of distillation.

Table 1 presents the vent gas composition with and without PSA (Cases A and B are without zero emission process). Due to bulk CO<sub>2</sub> removal, the emission components become

concentrated in the vent gas before the PSA (for example, for cases A and B the CO is in a range of 1000-3000 ppmv). For such high concentrations vent gas treatment become necessary. With zero emission these components (CO<sub>2</sub>, CO, NO<sub>x</sub>) become zero in purged vent gas stream. Table 1 shows that for the purified gases exiting from PSA compared to air, the O<sub>2</sub> is lower or the same and the Ar is much higher, and so this purified gas stream should not be forwarded to ASU for O<sub>2</sub> recovery. It is clear that the vent gas recirculation of zero emission enriches the inert gases in gas stream as shown by Table 1 (case-A to case-C & case-B to case-D), and is further enriched with low excess oxygen (case-C to case-F).

Table 1 presents the recirculation vent gas from the PSA to the boiler (with the assumption of no NO<sub>x</sub> conversion during SO<sub>x</sub> condensation), where N<sub>2</sub>, O<sub>2</sub>, and Ar are partly adsorbed with the emission components, (includes HCl, VOC, and SO<sub>x</sub>, and Hg not listed in Table 1). Due to separation of the N<sub>2</sub>, O<sub>2</sub>, and Ar from the vent gases, they are concentrated by about three times, which leads to CO<sub>2</sub> in the recirculation vent gas as high as 70-80% v, and very close to the CO<sub>2</sub> concentration in the original fluegas. Therefore, this vent gas could potentially be re-circulated directly to the CPU to enhance CO<sub>2</sub> capture. However, in the zero emission system the vent gas is re-circulated to the boiler because it achieves a simple, effective and economic closed-loop system for emission control.

Cases-B, D, E, & F have almost the same CO<sub>2</sub>%dv purity in raw gas to CPU. But differences in dry gas flow to CPU result in differences in specific CPU power. For the same raw gas CO<sub>2</sub> purity sealing boiler requires less CPU power than reducing excess oxygen (compare case D to case F in Table 1)

### **Effect of air ingress**

A big issue in oxyfuel combustion is the air ingress into the boiler since the efficiency of CO<sub>2</sub> removal is highly dependent on CO<sub>2</sub> purity. Air ingress increases not only CO<sub>2</sub> in the vent gas, but also increases power penalty for compression of the inert gases. The effect of air ingress has been widely evaluated in the literature as has the practicality of sealing the boiler. As shown by Table 1 for CO<sub>2</sub> removal, sealing the boiler can significantly reduce the specific power from 100% to 91.8% and increase the CO<sub>2</sub> capture efficiency from 91.1% to 96.3% (cases A and B). But on the other hand, it is also noted that the ASU power increases by 2.0% due to reduced O<sub>2</sub> contribution to combustion from the ingress air.

One of the objectives of the zero-emission is trying to maximize CO<sub>2</sub> capture in spite of the air ingress. To evaluate the effect from air ingress, 5% air ingress has been assumed as base case in model, while 2% air ingress has been applied for a tightly-sealed boiler. As shown by Table 1, with use of the zero-emission, 100% CO<sub>2</sub> capture is always obtainable in spite of the level of air ingress. At 5% air ingress, implementing zero emission (case-A to case-C), CO<sub>2</sub> capture efficiency is significantly increased from 91.1 to 100%, specific power is reduced from 100% to 95.3% with a 4.7% saving even as the relative CPU power is increased by nearly 10% due to the extra 10% CO<sub>2</sub> captured. The specific power can be further reduced from 95.3% to 90.1% if the air ingress can be reduced from 5% to 2% by a good boiler sealing (case C to Case E). With 2% air ingress, implementing zero emission (case-B to case-D) increases the CO<sub>2</sub> capture efficiency from 96.3% to 100% with a small gain in the specific power due to less inert gas flow. The

change in specific power savings for a change in air ingress from 5% to 2%, is reduced from 8.1% without zero-emission (case A to case-B) to 5.2% with zero-emission (case-C to case-D), which means the zero-emission system is less sensitive to the amount of air ingress than the non-zero-emission system.

### **Effect of low excess O<sub>2</sub> combustion**

In oxyfuel combustion, the fuel combustion is clearly enhanced by the high concentration of oxygen in feed, which benefits fuel burnout and so reduces UBC (unburned carbon). But because of high CO level in gas due to an equilibrium potential caused by combustion in a CO<sub>2</sub> environment, certain amount of excess oxygen needs to be maintained to suppress the CO concentration. Low excess oxygen combustion not only reduces oxygen requirement and ASU duty, but also reduces inert gases in CO<sub>2</sub> stream to CPU and thus the vent gas flow and CPU duty. Low excess oxygen reduces NO<sub>x</sub> but increases CO. With application of the zero-emission process, recycled CO and NO<sub>x</sub> undergo re-burn. In oxyfiring the over-firing air (OFA) is turned off due to needlessness of NO<sub>x</sub> control in furnace. As a result without the OFA and with increased O<sub>2</sub> level in feed, fuel burnout is enhanced. The 3-D furnace model simulations found that the UBC at 1% O<sub>2</sub> level without the OFA in oxy-firing is nearly the same as at 3% O<sub>2</sub> level with OFA in air-firing. Therefore the 1% O<sub>2</sub> level was used to evaluate the effect of lowering excess oxygen on the performance. At 5% air ingress, case-C to case-F show that the auxiliary power reductions, obtained by changing the O<sub>2</sub>% level from 3% to 1%, are 2.8% in ASU, 6.0% in CPU, and 3.6% in overall specific power. Changing the O<sub>2</sub> level from 3% to 1% increases the CO level from 3400 ppmv to 5100 ppmv (1600 ppmv air-firing) at furnace exit, and from 280 ppmv to 460 ppmv (154 ppmv air-firing) at boiler exit. Changing the O<sub>2</sub> level from 3% to 1% reduces the NO<sub>x</sub> level by 25%.

It is noted that case-F has almost the same specific power as case-B, which indicates that the use of the zero-emission process with 5% air ingress is equivalent to sealing the boiler to reduce air ingress from 5% to 2%. Furthermore, zero-emission increases CO<sub>2</sub> capture from 96% to 100% and reduces SO<sub>3</sub> formation by 30% (due to a reduction of O<sub>2</sub>%v from furnace exit gas), which helps reduce downstream corrosion. The overall advantage of the zero-emission is demonstrated by comparing case-A to case-F, where the CO<sub>2</sub> removal efficiency increases from 91.1% to 100%, and the specific power reduces from 100% to 91.7% for the same 5% air ingress.

### **CONCLUSIONS**

The raw gas from oxyfuel combustion to the CPU contains emission components. This raw gas must be treated to meet the end use requirement of the CO<sub>2</sub> stream. After purification, since the emission components of the vent gas are concentrated and at high pressure, an additional cost-effective purification process can be applied in conjunction with boiler emission reburn and recapture. This forms the basis of the zero-emission process which eliminates the emission of all gaseous and liquid pollutants.

True zero-emissions power generation can be achieved under the oxyfuel combustion if all of the product gases can be recirculated to the boiler, and undergo re-burn and re-capture within the closed-loop system. A new process has been investigated by Foster Wheeler, where all vent gas

streams from the downstream CO<sub>2</sub> purification unit (CPU) have been designed to flow back to the boiler. To avoid accumulation of nitrogen and argon (N<sub>2</sub>+Ar) in system, a pressure swing adsorption (PSA) process has been applied to the vent gas before recirculation, where purified (N<sub>2</sub>+Ar+O<sub>2</sub>) passes through the PSA, and the other gases, including part of the (N<sub>2</sub>+Ar+O<sub>2</sub>) regenerated from the adsorption process, are recirculated back to boiler.

The advantage of this zero-emissions process is that it achieves 100% CO<sub>2</sub> removal without increasing the ASU duty, and it performs a simple control to reach zero emissions through a closed-loop gas recirculation system. NO<sub>x</sub> control (including N<sub>2</sub>O) does not require any conventional deNO<sub>x</sub> processes, such as SCR or SNCR, and it potentially relaxes the requirements for combustion staging. It allows the boiler to be operated at low excess oxygen in spite of CO level due to re-burn effect from gas recirculation, which significantly reduces the overall CO<sub>2</sub> removal specific power from 100% to 91.7% for 5% boiler air ingress. Because of downstream PSA gas separation, it does not require high efficiency emission control equipment for tight emission control. It relies on the boiler and scrubber as well as gas recirculations in oxyfuel combustion to reach the zero-emissions. This approach is applicable for both Greenfield and retrofit applications.

In summary, the zero-emission process reaches

- 1) 100% CO<sub>2</sub> removal
- 2) A relatively low specific power per CO<sub>2</sub> removed
- 3) True zero-emissions
- 4) A simple and economic way to get zero-emissions

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