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Chemical and Process Engineering 2015, 36 (4), 405–423
DOI: 10.1515/cpe-2015-0029
PAN POLSKA AKADEMIA NAUK

ERRORS ASSOCIATED WITH EXCESS AIR MULTIPOINT MEASUREMENT SYSTEMS

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Boiler combustion air is generally controlled by the excess air content measured at the boiler economiser outlet using oxygen (O_2) analysers. Due to duct geometry and dimensions, areas of high and low O_2 concentrations in the flue gas duct occur, which poses a problem in obtaining a representative measurement of O_2 in the flue gas stream. Multipoint systems as opposed to single point systems are more favourable to achieve representative readings. However, ash blockages and air leakages influence the accuracy of O_2 measurement. The design of multipoint system varies across ESKOMs' Power Stations. This research was aimed at evaluating the accuracy of the multipoint oxygen measurement system installed at Power Station A and to determine the systematic errors associated with different multipoint systems designs installed at Power Stations' A and B. Using flow simulation software, FloEFD™ and Flownex®, studies were conducted on two types of multipoint system designs This study established that significantly large errors, as high as 50%, were noted between the actual and measured flue gas O_2. The design of the multipoint system extraction pipes also introduces significant errors, as high as 23%, in the O_2 measured. The results indicated that the sampling errors introduced with Power Station A's system can be significantly reduced by adopting the sampling pipe design installed at Power Station B.

Keywords: Excess air measurement; flue gas oxygen concentration, boiler O_2, air ingress

1. INTRODUCTION

1.1. Importance of excess air in boilers

State-owned power utility, Electricity Supply Commission (ESKOM), has been generating, transmitting and distributing electricity to the African continent for the past nine decades. ESKOM generates approximately ninety-five percent of the electricity used within South Africa (ESKOM, 2013). Electricity can be produced from a range of primary energy resources, and due to its abundance, coal plays a vital role in electricity generation worldwide. ESKOM currently depends on thirteen coal-fired power stations to generate approximately ninety percent of its electricity.

Boiler excess air is of great importance for optimal combustion but must be controlled within acceptable limits. Less air prevents all the combustibles in the fuel from being burnt; resulting in wasted fuel. An increase in the production of carbon monoxide (CO) is expected due to incomplete combustion of the carbon

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contained in the fuel; creating a potential for explosion. Furthermore, the reducing atmosphere increases the propensity of ash to slag and foul the boiler heat transfer surfaces (Bhatt, 2007). Conversely, too much air increases the flue gas velocity which increases the erosion rate of boiler components. The resultant increase in the flue gas volume flow rate decreases the performance of gas cleaning systems, specifically those used for particulate removal. An increase in the auxiliary power requirements can be expected mainly due to an increase in the forced draught and induced draught fan power consumption to supply and extract the air-gas from the boiler system which will limit the generating capacity of the unit (Van Wyk, 2007). Furthermore, the additional air acts as a dilutant without any useful purpose and exacerbates the heat loss from the boiler which negatively impacts on the combustion efficiency (Bhatt, 2007).

With reference to Fig. 1, the combustion efficiency is optimised when the right mixture of fuel and air is supplied to minimise the energy losses associated with excess fuel and excess air (Molloy, 1981).

The most effective approach with a coal-fired boiler is to control the flue gas O_2 level to a point where optimum combustion efficiency is attained whilst ensuring that the flue gas CO (ppm) content does not come close to the CO breakthrough point at which a sudden increase in CO will occur as a result of incomplete combustion (Innami et al., 2011). One way of controlling the amount of excess air is by directly measuring the residual O_2 content in the flue gases. It is therefore necessary to ensure continuous, reliable and accurate measurement of the O_2 concentration in the flue gas to optimise the combustion process and to maintain the boiler efficiency.

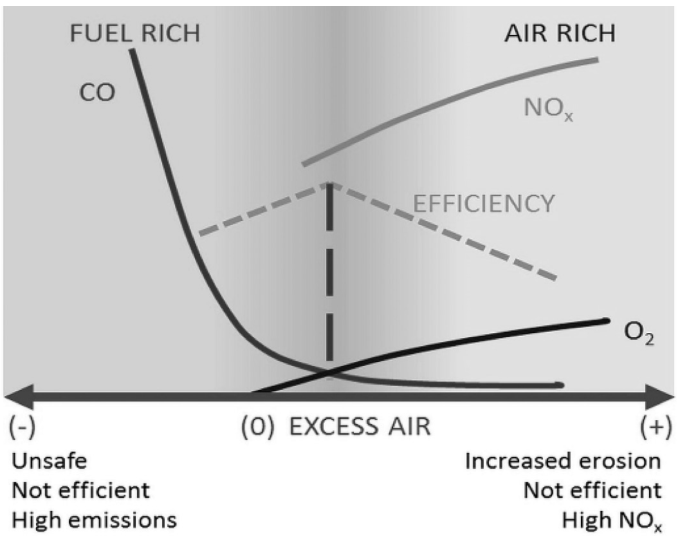


Fig. 1. Schematic of relationships between excess air, fuel and combustion efficiency (Yokogawa, 2008)

1.2. Deficiency identification

O_2 analysers are essential boiler instrumentation used to measure the excess air and provide critical feedback to operators for combustion control. These are either installed directly into the flue gas stream as a single point measurement or as part of the multipoint measurement system. However, due to mill configuration and arrangement of burners, maldistribution of pulverised fuel occurs. This leads to uneven combustion which produces areas of high and low gas concentrations in the furnace, referred to as stratification. This condition propagates throughout the gas path, and due to duct dimensions and geometry, thorough mixing of the flue gas is prevented. Furthermore, air ingress along the ducting system only aggravates this situation which poses a problem in obtaining a representative measurement of O_2. Therefore multipoint systems are more favourable than single point measurement systems despite the common problems associated with multipoint systems, such as ash blockages and air leakages, influence the accuracy of O_2 measurement.

Research across ESKOM's Power Stations has indicated that more focus has been placed on modifying the current installed multipoint systems to reduce blockage and wear, and as a result, the design of the multipoint system varies from station to station especially in terms of the diameter of the extraction ports, diameter of the pipes, the orientation of the extraction ports (facing the flue gas flow, facing away from the flow or perpendicular to the flow), and in the flue gas extraction method. Although a tremendous amount of effort and emphasis has been placed on modifying these systems, a thorough search of the literature available revealed no documented information on sampling errors associated with these different multipoint system designs. Apart from flue gas stratification, research has also shown that some of the contributory factors to erroneous O_2 measurement are O_2 analyser calibration, deterioration in the performance of the zirconium cell due to age, fly ash build up in the cell's filter and pressure induced drift (Scott and Dennis, 2010).

1.3. Specific objectives of this study

The primary objectives of this research are to determine the following:

a) Evaluate the accuracy of the multipoint oxygen measurement system installed at Power Station A
b) Determine the systematic errors associated with different multipoint systems designs.

2. BACKGROUD AND LITERATURE REVIEW

2.1. Power Station A measurement system

Power Station A is a large coal-fired power station consisting of six, 618 MW units, generating a total of 3708 MW. The oxygen measurement system is located at the rear of the boiler, at the economiser outlet ducts, which splits into two and are generally referred to as the left hand (LH) and right hand (RH) ducts (see Fig. 2). An O_2 measurement system is installed in each duct.

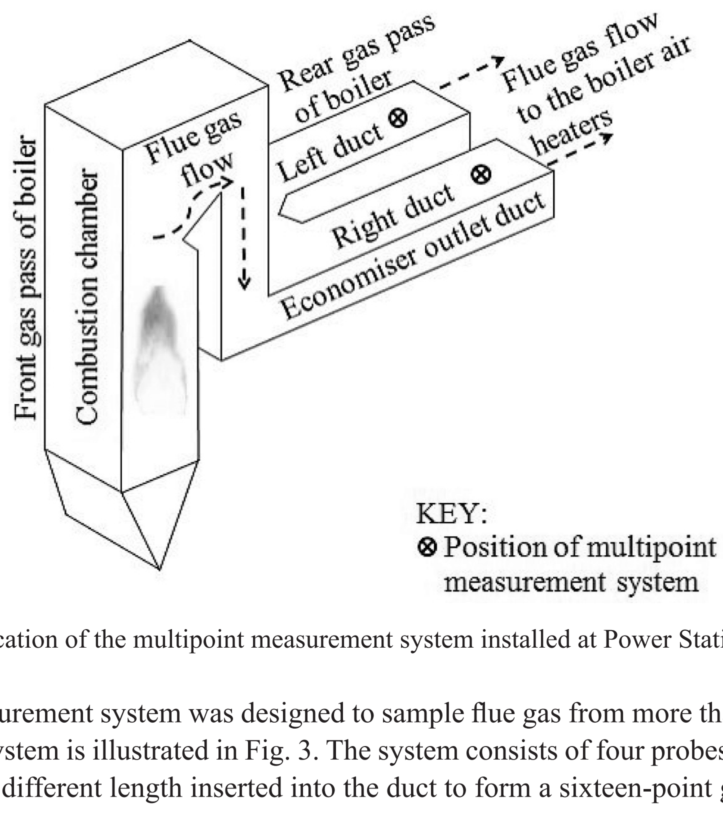


Fig. 2. Location of the multipoint measurement system installed at Power Station A

The multipoint measurement system was designed to sample flue gas from more than one point in a duct. A schematic of the system is illustrated in Fig. 3. The system consists of four probes, each with four mild-steel square pipes of different length inserted into the duct to form a sixteen-point grid measurement.

A sample of flue gas is extracted on a continuous basis through the opening located at the bottom of each pipe. These pipes combine into a common pipe situated outside the duct. The combined flue gas sample is directed to a zirconium ceramic analyser which measures the O_2 content.

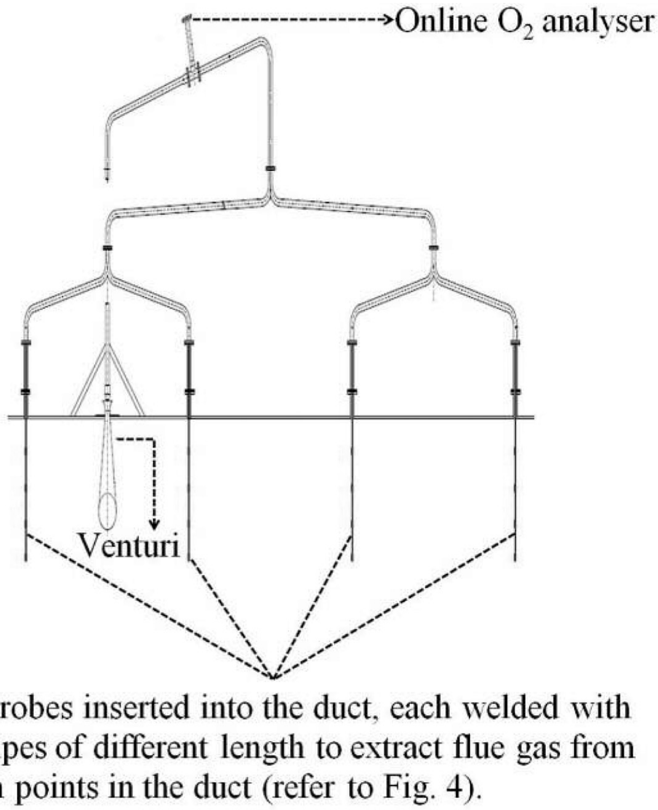


Fig. 3. Schematic of a sixteen-point measurement system installed at Power Station A

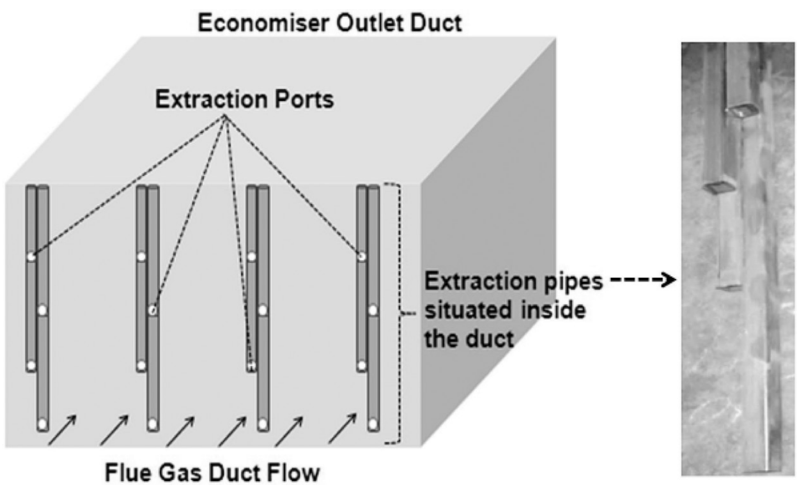


Fig. 4. Power Station A's multipoint extraction pipe (front view)

The sample flow is generated by a venturi arrangement located at the top of the flue gas duct, drawing the sample back into the duct in the process. The pressure differential between the low pressure duct and atmosphere drives the flow through the venturi. The entire system is insulated to maintain the temperature of the flue gas to prevent moisture in the flue gas from combining with the ash and thereby prevent ash from settling in the pipes and creating a blockage. The system has 'purge points' through which air is blown to remove and clear blockages and also a test point located after the O_2 analyser which is used to verify the O_2 reading between a portable O_2 analyser and the online O_2 instrument.

2.2. Processing of the O_2 signal

A simplified illustration of processing the O_2 signal is shown in Fig. 5. The signal from the O_2 analyser located on each multipoint measurement system is directed to the equipment room. Thereafter, this signal is fed to the online plant data system, where it is recorded. The unit operator uses this O_2 reading to manually adjust the boiler excess air. Incorrectly measured O_2 can result in the operator either supplying too much or too little excess air.

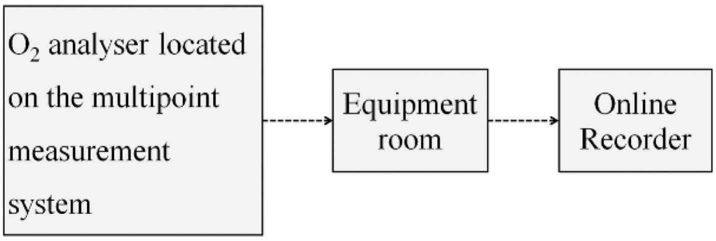


Fig. 5. Simplified illustration of O_2 signal processing

2.3. Literature review

It was established that 60% of ESKOM's power plants have multipoint measurement systems installed. The systems were also verified for compliance with ESKOMs' Fossil Fuel Firing Regulations (FFFR) which stipulates that the "Boilers with split flue gas outlets shall have at least two oxygen analysers per boiler flue gas pass before the airheaters. Boilers with a single gas pass outlet shall have at least three oxygen analysers on the flue gas duct before the airheaters" (ESKOM, 2014).

2.3.1. Types of O_2 analysers installed in Eskom

Yokogawa is the leading supplier of the oxygen analysers, supplying ESKOMs' ten coal-fired power plants. Other suppliers include ABB, Rosemount and Servomex. There are four different sampling techniques used to measure flue gas with a zirconium oxide sensor. These sampling techniques include the in-situ, close-coupled extractive, extractive, and convective method. The most common techniques employed within ESKOM are the in-situ and the close-coupled extractive. With regards to the in-situ analyser, the probe is inserted directly into the flue gas duct, with the zirconium oxide cell located at the tip of the probe. These analysers are the preferred as they can be directly inserted into the hot flue gases with high ash content, with no conditioning of the sample required.

2.3.2. Multipoint measurement systems

Power Station B, which has eight generating units, each with an installed capacity of 200 MW, generating a total of 1600 MW, has a multipoint measurement installed at the economiser outlet duct that is similar to the system installed at Power Station A, with exception to the design of the extraction pipes, through which the flue gas samples are extracted.

The design of each set of extraction probes used at Power Station A consists of four pipes of different lengths (termed "segregated sampling"), whereas, each set of extraction probes used at Power Station B consists of one pipe with four circular cut-out extraction ports located on one pipe (termed "common sampling"). These two designs are illustrated in Figs. 6 (a) and (b).

This research aims to compare the designs of the extraction pipes used at Power Stations' A and B and to determine the error in O_2 measurement associated with both configurations.

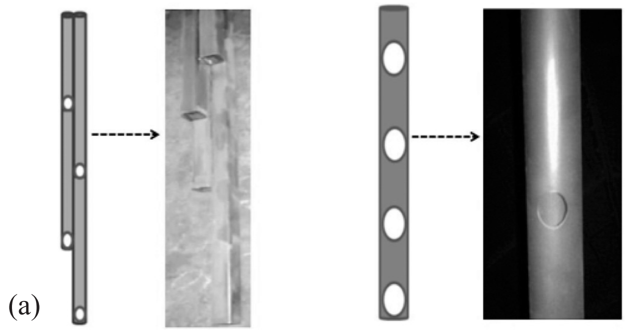


Fig. 6. Multipoint extraction pipes: (a) Power Station A’s design (segregated sampling), (b) Power Station B’s design (common sampling)

3. RESEARCH METHOD

This chapter presents the test equipment, method of sampling, test work and analyses carried out for the following:

- Power Station A's traverse tests (section 3.1)
- Systematic O_2 errors associated with Power Stations' A and B extraction pipe designs (section 3.2)

3.1. Power Station A's traverse tests

Traverse tests were carried out at Power Station A to determine the flue gas velocity (m/s), O_2 (%), CO (ppm) and temperature (in ^oC) profile across the boiler outlet ducts in accordance with the British Standard, ISO 16911-1:2013, to determine the true average O_2 of the duct.

An S-type calibrated Pitot tube was used to measure the flue gas static and differential pressures at the economiser outlet. A calibrated flue gas analyser (Testo 340) was used to measure the flue gas constituents (O_2, CO) concentration. The flue gas temperature profile was measured using a K-Type thermocouple.

The test program included three traverse tests carried out on Unit 3, boiler economiser outlet ducts. Tests “1”, “2” and “3” were conducted at boiler O_2 levels of 1.5%, 2% and 2.5% respectively. The measurements were taken from the top to the bottom of the duct (along the depth) and from LH to RH (along the length of the duct). At each point in the duct, at 5-minute intervals, the O_2, CO, temperature, dynamic pressure, and static pressure were measured (refer to Fig. 7).

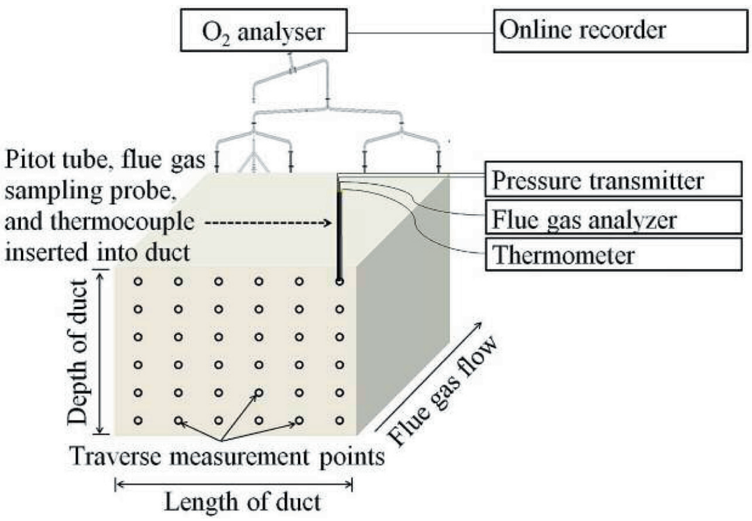


Fig. 7. Schematic of the flue gas duct and sampling probes (measured data)

A total of thirty six points were measured per LH and RH duct. The O_2 recorded on the online plant data system was simultaneously logged at 5-minute intervals.

The percentage error difference between the different readings is calculated according to the following formula:

$$\%\ \text{Error difference} = X_{O_2} = \frac{\mathrm{O}_{2,r} - \mathrm{O}_{2,m}}{\mathrm{O}_{2,m}} \times 100 \tag{1}$$

These traverse test results were applied in section 3.2 to analyse the system errors associated with different multipoint system designs.

3.2. Systematic O_2 errors related to different multipoint designs

The multipoint extraction pipes installed at Power Stations' A and B have two distinct designs. Studies on both designs were performed with the aid of a one dimensional network solver, viz. Flownex. This simulation software was used to determine the sampling inaccuracies of both designs by evaluating the sampling errors introduced when parameters such as the extraction pipe length, pipe diameter, extraction port diameter, and the duct velocity distribution were varied. The results from the traverse tests provided the inlet boundary conditions for the multipoint system; although the outlet boundary conditions, viz. the multipoint outlet pressure, was unknown. There were no measurement ports available on the system to measure the pressure at the outlet of the system and as a result, FloEFD, a 3D computational fluid dynamics (CFD) software package, was used to predict the outlet pressure of Power Station A's multipoint system.

3.2.1. Predicting the outlet pressure of the multipoint system

Figure 10 illustrates the iterative process used to determine the outlet pressure of the multipoint system. The flow through the multipoint system is created and maintained by a venturi. The venturi, together with 100 mm of the multipoint system pipe and flue gas duct was modelled in FloEFD (refer to Fig. 8), whilst the sixteen-point system was modelled in Flownex (refer to Fig. 9). The flue gas velocity, pressure and temperature measured during the traverse tests were applied as the boundary conditions. As a point of reference, since the pipe inlet pressure was unknown, it was initially assumed to be just below the duct pressure. The iteration process, described in Fig. 10, continued until the mass flow rates through the multipoint system and the venturi were within 0.05% of each other. The final estimated pipe inlet pressure was then applied as the outlet boundary condition in Flownex. With the inlet and outlet boundary conditions now known, the parameter study was done.

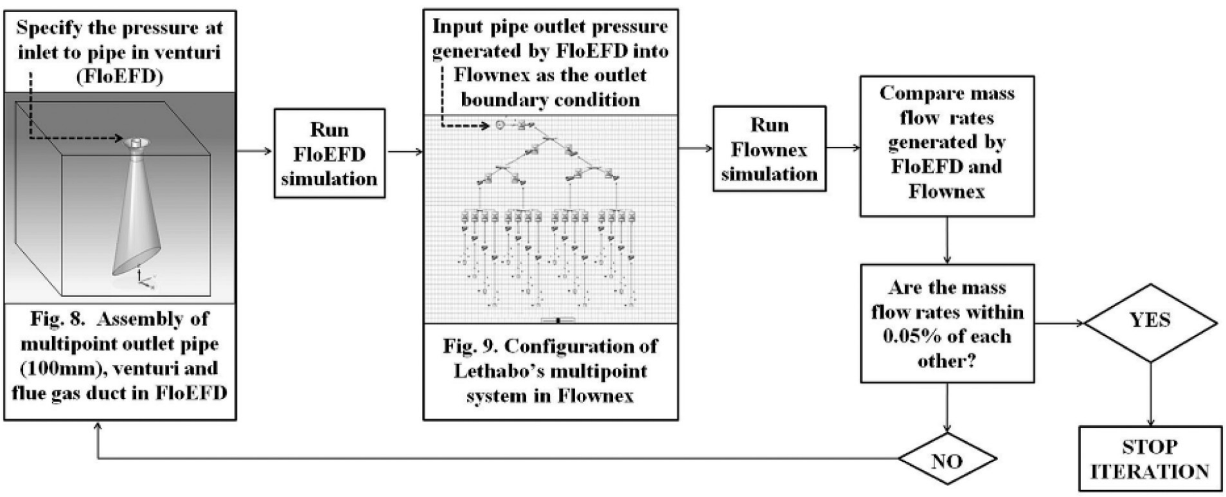


Fig. 10. Iterative process between FloEFD and Flownex to determine the outlet pressure of the multipoint system

3.2.2. Parameter study

The theoretical study was done for both multipoint extraction pipe designs positioned in the same duct. With reference to Fig. 11, the entire multipoint measurement system consists of four sets of extraction pipes positioned at four locations across the length of the duct to form a sixteen-point sampling system across the duct.

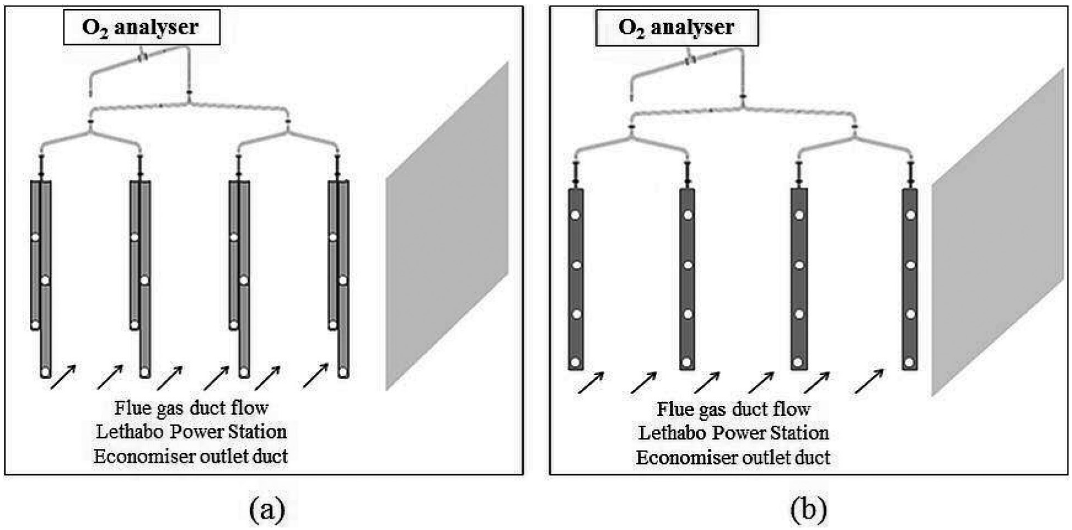


Fig. 11. Extraction pipes positioned in Power Station A's duct: (a) Power Station A's system (segregated sampling), (b) Power Station B's system (common sampling)

The configuration of each set of extraction pipes used at Power Station A consists of four individual pipes; each pipe having a different length along the depth of the duct with an opening at the bottom of each pipe (refer to Fig. 4) through which flue gas is extracted and sampled. This type of arrangement is referred to as "segregated sampling". The configuration of the extraction pipe used at Power Station B consists of a single pipe with four extraction ports positioned at different points along the vertical depth of the pipe and is referred to as "common sampling".

The systematic error analysis was first done using just two extraction points per segregated and common sampling pipe design and thereafter a full study was done on the sixteen-point multipoint system. Details of the different studies completed are listed in Table 1.

3.2.2.1. Two-point study

The first two-point study was done on the segregated sampling pipe configuration as illustrated in Fig. 12. The pressure, temperature and pipe geometry for pipe 1 and 2 were initially set to be identical. Two arbitrary O_2 measurements were chosen from across the three sets of traverse tests and were used as the inlet boundary conditions for point 1 and 2, while the pressure at the outlet boundary condition was determined from the iteration process between FloEFD and Flownex (discussed in section 3.2.1).

The mass weighted average O_2 concentration for this condition was calculated as per the equation below and served as the reference O_2.

$$\bar{x}_{O_2} = \frac{\dot{m}_1 \, x_{O_{2,1}} + \dot{m}_2 \, x_{O_{2,2}}}{\dot{m}_1 + \dot{m}_2} \tag{2}$$

Thereafter, the length for pipe 1 was varied whilst the length for pipe 2 remained constant and vice versa. Each time the length was varied, a new mass weighted average O_2 was calculated.

The percentage error incurred between the reference and new average O_2 was calculated. A similar analysis was done at different pipe diameters.

The effect of an imbalance in duct flow on O_2 sampling was also examined and the error from the reference O_2 was calculated. The duct flow distribution factors, simulating the effect of an uneven velocity profile, were introduced as per the equation below:

$$\bar{x}_{O_2} = \frac{K_1 \dot{m}_1 x_{O_{2,1}} + K_2 \dot{m}_2 x_{O_{2,2}}}{\dot{m}_1 + \dot{m}_2} \tag{3}$$

Table 1. Details of studies completed per system design

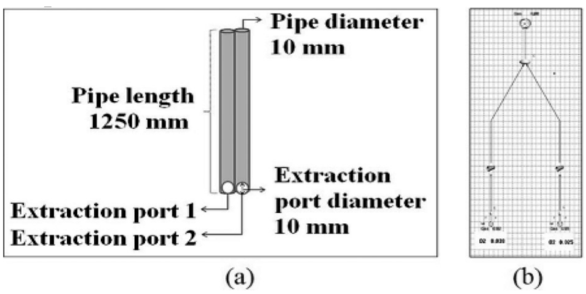
<table>
<tr><th>Segregated sampling</th><th>Common sampling</th></tr>
<tr><td colspan="2">Two-point study</td></tr>
<tr><td>a. Varied length of pipes
b. Varied diameter of pipes
c. Varied approach gas velocity to extraction port 1 and 2


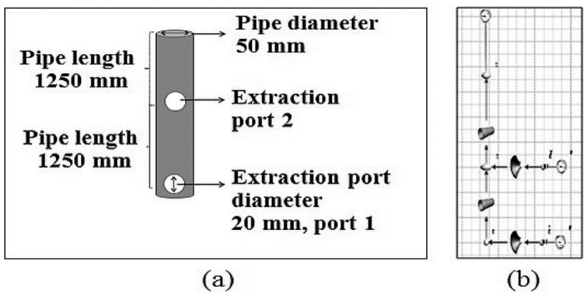
Fig. 12. (a) Schematic of Power Station A's two-point measurement, (b) Flownex model</td>
<td>a. Varied orifice diameter
b. Varied the pipe diameter
c. Varied approach gas velocity to extraction port 1 and 2


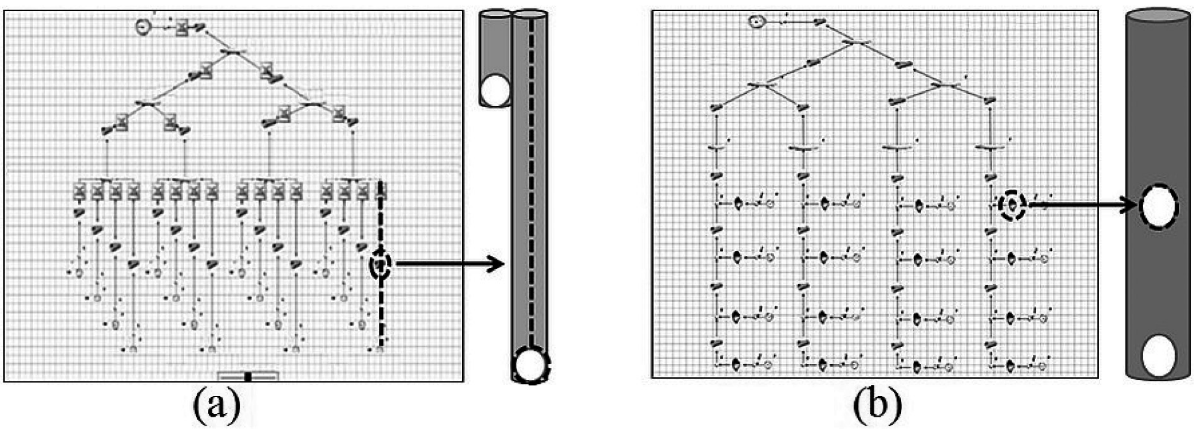
Fig. 13. (a) Schematic of Power Station B's two-point measurement, (b) Flownex model</td></tr>
<tr><td colspan="2">Sixteen-point study</td></tr>
<tr><td colspan="2">a. Configured the sixteen-point measurement in Flownex for both designs (see Fig. 14).
b. The O_2, temperature and total pressure, measured during the traverse tests was applied as the inlet boundary condition to each extraction point.
c. Established the error between the O_2 calculated by Flownex and the velocity-weighted O_2 measurement in the actual duct.


Fig. 14. Sixteen-point multipoint arrangement in Flownex, (a) segregated sampling pipe design (b) common sampling pipe design</td></tr>
</table>

Table 2 lists the duct flow distribution factors which were applied to the results of above-mentioned two sub-studies (varying length and pipe diameter). These factors were established by assuming the duct flow is halved, equal and then doubled.

The traverse test average duct velocity was measured to be 12.5 m/s. A minimum (7 m/s) and maximum (25 m/s) flow distribution was applied to pipe 1 whilst the distribution for pipe 2 remained even and vice versa. It should be noted that the minimum and maximum velocity measured during the traverse tests were 7 m/s and 19 m/s, respectively. As per the two-point study done on the segregated sampling pipe design, a similar analysis was done on the common sampling pipe design, by varying the orifice diameter, pipe diameter and the duct flow distribution (details are listed in Table 1).

Table 2. Duct flow distribution factors

u_1 (m/s)	u_2 (m/s)	$u_1/u_2 = K_1$	$u_2/u_1 = K_2$
7.10	12.5	0.57	1.00
12.5	12.5	1.00	1.00
19.6	12.5	1.57	1.00
25	12.5	2.00	1.00

3.2.2.2. Sixteen-point study

The final study was done on the full sixteen-point multipoint system for both sampling pipe configurations (see Fig. 14). The input boundary conditions applied to the sixteen-point system were determined from the traverse test measurements. The pressure, temperature and O_2 measured per point were then applied as the inlet boundary conditions in Flownex. Simulations were completed for each duct over the three days. The O_2 calculated by Flownex, for both sixteen-point configurations were then compared to the velocity-weighted O_2 average determined from the traverse tests for each duct and the percentage error was determined for both designs, for all three sets of tests.

4. RESULTS AND DISCUSSION

The results of the following are discussed in this chapter:

- Power Station A's traverse tests (section 4.1)
- Systematic O_2 errors associated with Power Stations' A and B extraction pipe designs (section 4.2).

4.1. Traverse test results

A comparison between the O_2 recorded on the system and the traverse test measured O_2 are illustrated in Fig. 15. As previously discussed, the 'recorded O_2' serves as a critical indication to the boiler operator as the boiler operator uses this indication to manually adjust the excess air necessary for complete combustion.

Figure 15 illustrates that the traverse test measured O_2 was constantly lower than the recorded O_2 across all three tests. One of the contributory factors to this condition was due to the air leaks found on both multipoint systems around the purge points which were not properly sealed. This resulted in ambient air entering the system, thereby increasing the flue gas O_2 concentration measured by the O_2 analyser. Errors between the recorded O_2 and the measured O_2 were as high as 50% for test "2", LH duct; giving the operator a false indication that there was sufficient air available for complete combustion and therefore resulted in less air being supplied to the boiler and incomplete combustion.

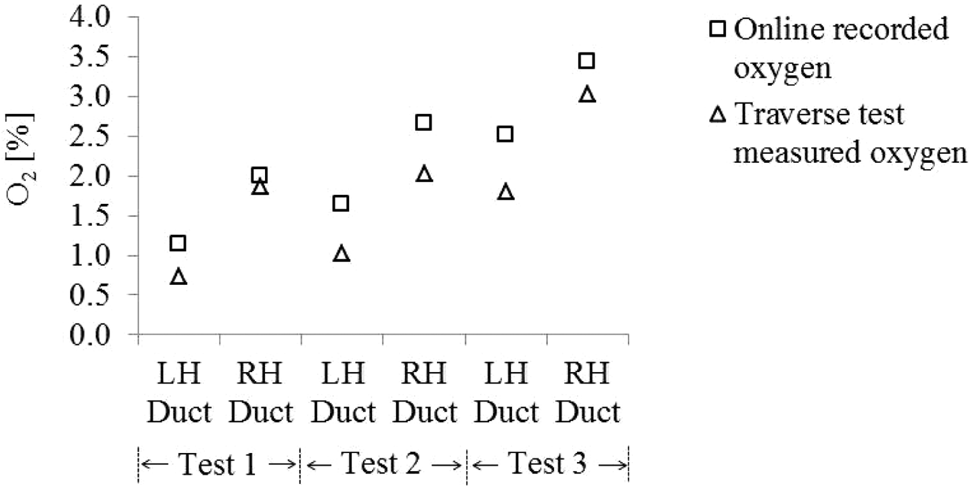


Fig. 15. Comparison between 'recorded O_2' and 'measured O_2'

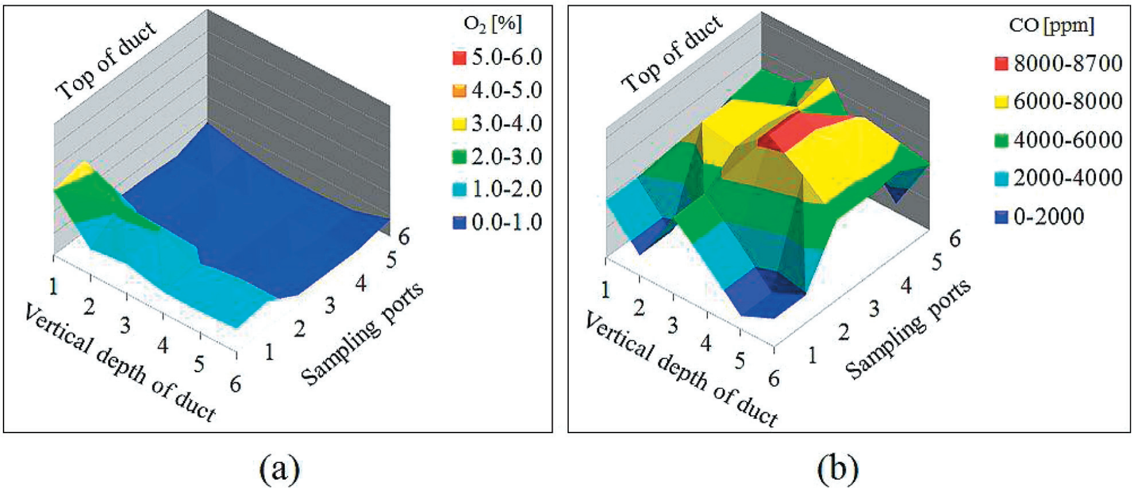


Fig. 16. Power Station A, test 1, left duct: (a) O_2 profile (%), (b) CO profile (ppm)

This condition was evident as the traverse test measurements indicated high CO concentrations in the flue gas duct, with CO peaking at 8600 ppm for test "1", LH duct (see Fig. 16 (b)). Apart from air ingress on the multipoint system, it was also established that the design of the multipoint extraction pipes contributed to the discrepancy in measurements. Different studies on the system design were completed using Flownex. The results are further discussed in section 4.2.

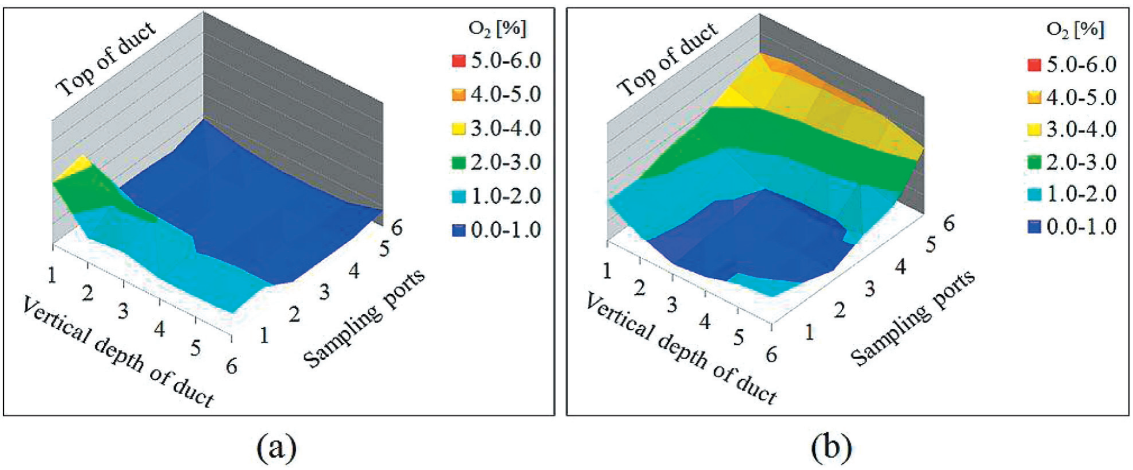
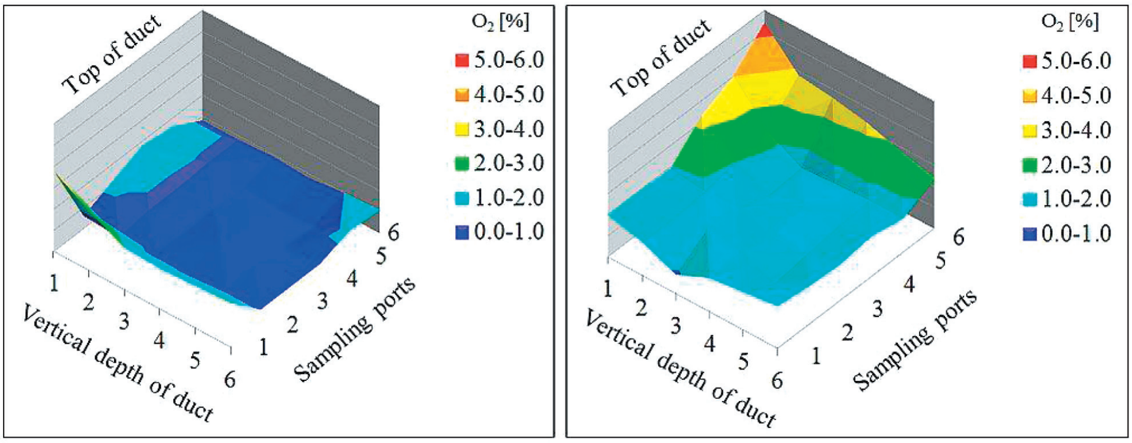
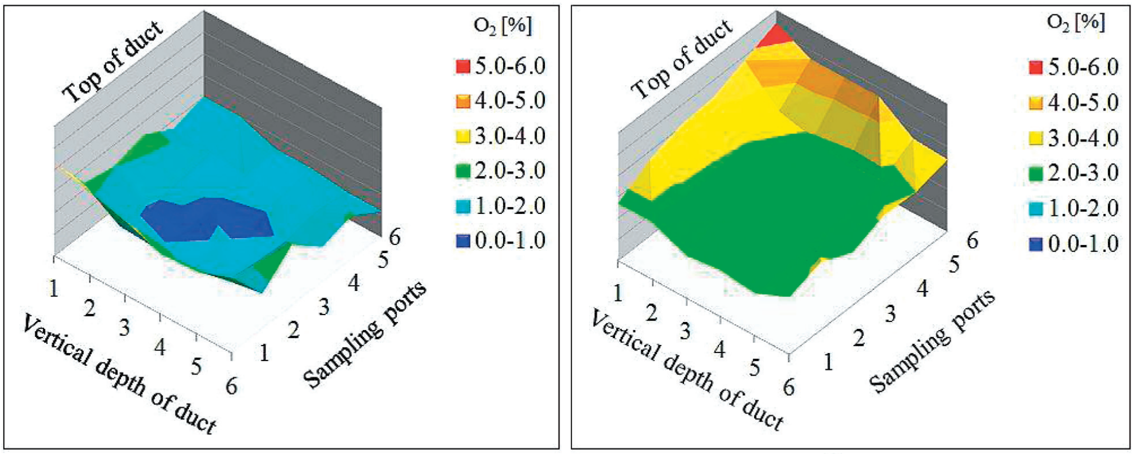


Fig. 17. Power Station A, O_2%, test 1: (a) LH duct, (b) RH duct



(a) (b)

Fig. 18. Power Station A, O_2%, test 2: (a) LH duct, (b) RH duct



(a) (b)

Fig. 19. Power Station A, O_2%, test 3: (a) LH duct, (b) RH duct

It can also be seen in Fig. 15 that there was a noticeable imbalance between the two ducts for each test. Higher O_2 concentrations were measured on the right duct when compared to the left. This condition was due to a suspected air leak (air ingress) on the right duct. The O_2 distribution pattern remained the same for tests "1", "2", "3", with higher O_2 concentrations measured along the side walls of the duct and lower O_2 towards the centre of the duct (refer to Fig. 17 to Fig. 19).

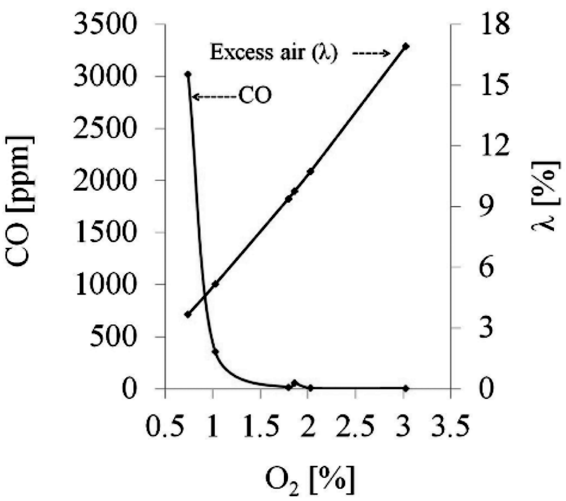


Fig. 20. CO (ppm) versus O_2 (%)

Furthermore, the temperature distribution pattern also remained the same for all three sets of tests, with lower temperatures towards the side walls and higher temperatures towards the centre of the duct. The average O_2 and CO measured per duct for tests "1", "2" and "3" are illustrated in Fig. 20. It can be seen that when operating just below 1.5% O_2, there is a substantial production of CO in the flue gas, averaging 3000 ppm on the LH duct, for test "1". This is typically referred to as the "CO breakthrough point", and as the O_2 increases from 1.5% to 2% O_2, the CO produced immediately reduces to below 50ppm, which is within the safe operating limit of 200 ppm.

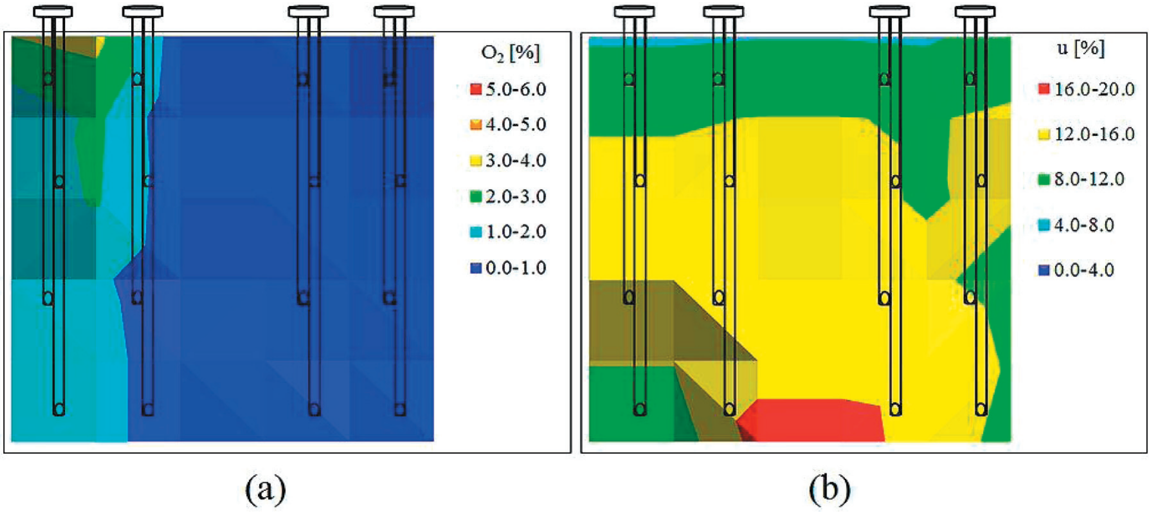


Fig. 21. Power Station A, test 1, LH duct: (a) O_2 profile (%), (b) velocity profile (m/s)

Table 3. Percentage deviation between min and max O_2 per duct

Flue gas duct	Test 1	Test 2	Test 3
Flue gas O_2			
Left Duct	177%	162%	137%
Right Duct	158%	143%	92%
Flue gas velocity			
Left Duct	79%	78%	74%
Right Duct	72%	72%	71%

Figure 21 represents a 2D contour plot of oxygen and flue gas velocity in the same duct in relation to the multipoint extraction pipes located in the duct.

It is evident that flue gas O_2 and velocity maldistribution exists, with areas of high and low O_2, together with areas of high and low velocities in the same duct, thereby substantiating that a multipoint measurement system is more favourable than a single point measurement. The percentage deviation from average between the minimum and maximum O_2 and flue gas velocity measured per duct per test are listed in Table 3.

It is noted that as the excess air increases (test "1" to test "3"), the percentage deviation between the minimum and maximum O_2 per duct improves from 177% down to 137% and from 158% down to 92% for the left and right ducts respectively. A similar trend can be seen with the flue gas duct flow distribution as the deviation between the minimum and maximum velocity measured per duct improves from 79% and 72% to 74% and 71% for the left and right ducts respectively as the excess air increases. The effect of duct velocity maldistribution, which formed part of the Flownex study, indicated that velocity stratification has the largest impact on accurate measurement of O_2 and the results are further discussed in section 4.2.

4.2. Systematic O_2 error of different multipoint system designs

The following results are discussed in this chapter:

- Calculation of the multipoint outlet pressure using FloEFD and Flownex
- Two-point simulation for segregated and common sampling pipe design using Flownex
- Full sixteen-point simulation for segregated and common sampling pipe design using Flownex

4.2.1. Multipoint outlet pressure calculation

The resultant pipe outlet pressure was determined to be 84175 Pa, whilst the mass flows generated by Flownex and FloEFD were within 0.05% of each other. This calculated pipe outlet pressure was used as the outlet boundary condition in all further sub-studies carried out in Flownex.

4.2.2. Two-point study

4.2.2.1. Segregated sampling pipe design

The results of the three sub-studies applied to the two-point configuration (refer to Table 1), for segregated sampling pipe design are discussed below.

a) Sub-study 1: Varied pipe lengths

Fig. 22 illustrates the error in O_2 as the pipe length is varied. Due to the higher flow resistance incurred as the pipe length is increased from 1025 mm to 4025 mm, the error in O_2 increases to 9.1%.

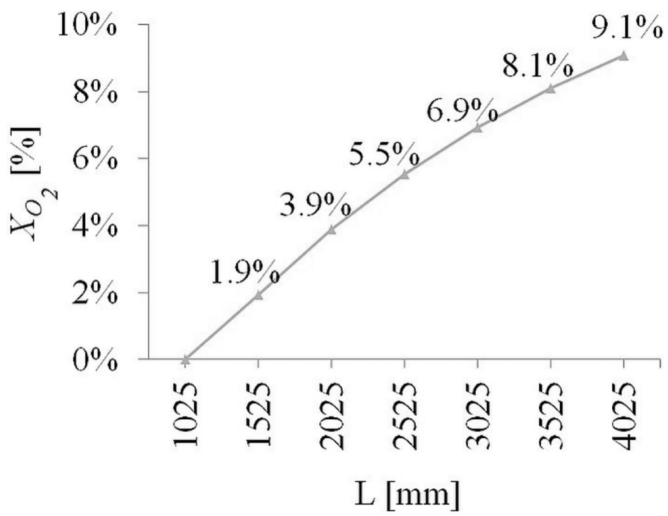


Fig. 22. Sampling error with change in pipe length

b) Sub-study 2: Varied pipe diameters

The error in O_2 incurred as the pipe diameter was varied from 10 mm to 50 mm is illustrated in Fig. 23.

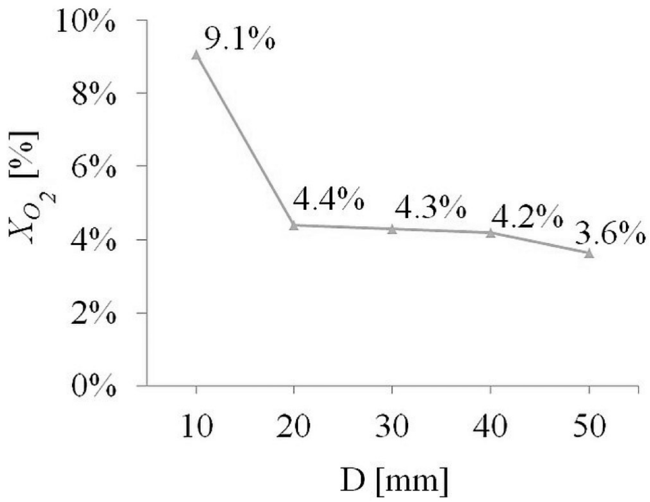


Fig. 23. Sampling error with change in pipe diameter

It can be seen from Fig. 23 that as the pipe diameter is increased from 10mm to 50mm, the O_2 error of 9.1% reduces to 3.6% due to the reduction in the pipe friction loss; thereby reducing the resistance to flow in a larger pipe and increasing the mass flow of flue gas. It can also be seen that increasing the pipe diameter from 10 mm to 20 mm yields a significant reduction in error, i.e. 50%, and further reduces as pipe diameter is increased.

c) Sub-study 3: Varied the duct flow distribution

The third sub-study was done to determine impact of varying the flue gas flow distribution through pipe 1 and pipe 2 at different lengths. Fig. 24 indicates that as the duct flow is varied from nearly half to double for pipe 1, whilst keeping the gas flow across pipe 2 constant, substantial errors ranging from –30% up to 46% are incurred. It can also be seen that as the flow velocities across both pipes equalises (distribution factor of 1), the errors incurred become less significant. These trends are applicable to the pipe diameter of 10 mm. Similar trends can be seen for pipe diameters of 20 mm up to 50 mm.

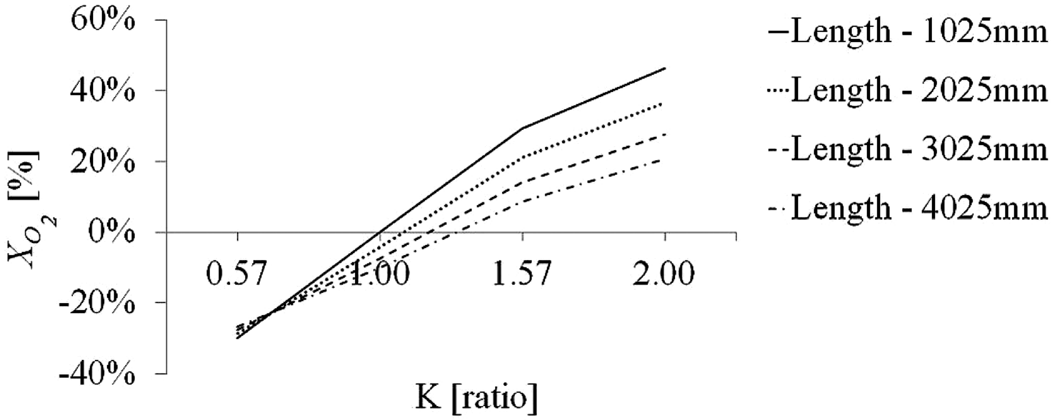


Fig. 24. Sampling error with change in duct flow distribution – Pipe 1 (10 mm sampling diameter)

4.2.2.2 Common sampling pipe design

a) Sub-study 1: Varied sampling port diameter

It can be seen from Fig. 25 that the error in O_2 increases exponentially to 2.5% when the extraction port diameters increases from 10 mm to 40 mm. This is as a result of an increase in the friction losses along the pipe, which hinders mass flow through the extraction ports and affects the overall average O_2 concentration.

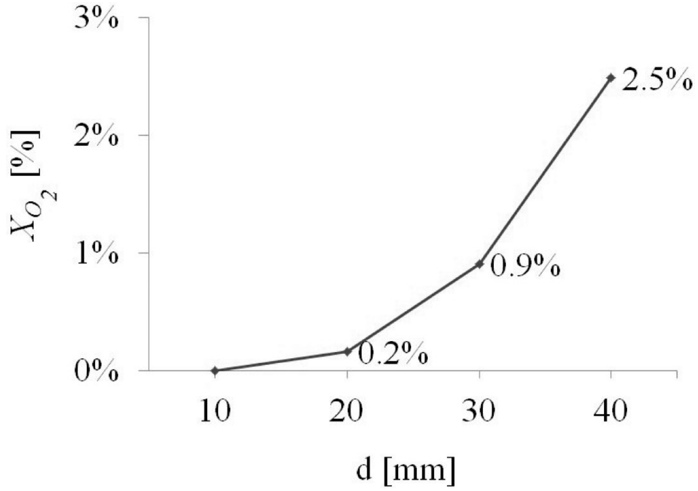


Fig. 25. Sampling error with change in extraction port diameter

b) Sub-study 2: Varied pipe diameter

The first sub-study discussed above was done on a pipe diameter of 50 mm whilst varying the extraction port diameters. The second sub-study included keeping both extraction port diameters constant at 10mm and varying this pipe diameter from 20 mm to 50 mm. Figure 26 illustrates that as the pipe diameter is increased the error in O_2 is reduced substantially due to the lower resistance to flow in the larger pipe, equalising the mass flow rate through ports 1 and 2.

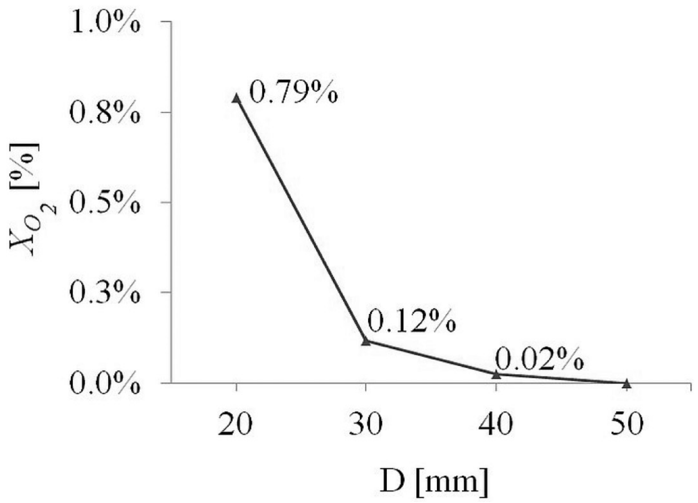


Fig. 26. Sampling error with change in pipe diameter – Ports 1 and 2

c) Sub-study 3: Varied the duct flow distribution

Similar to the study carried out on the segregated two-point sampling pipe design, the third sub-study was to determine the impact of varying the flue gas flow distribution through pipe 1 and pipe 2 at different extraction port diameters. With reference to Fig. 27, as the gas velocity is varied from nearly half to double for extraction port 1, whilst keeping the gas velocity across extraction port 2 constant, significant errors of between -30% and 46% are introduced. As the flow distribution across both pipes equalises (distribution factor of 1), the errors incurred become less significant.

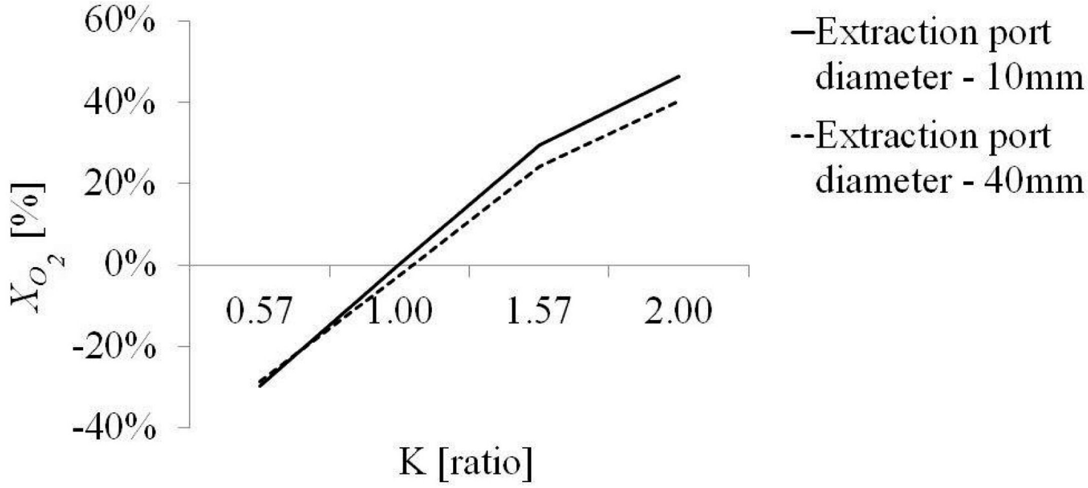


Fig. 27. Sampling error with change in duct flow distribution – Port 1 (50mm pipe diameter)

4.2.3. Sixteen-point study

The results of traverse tests "1", "2" and "3" provided the inlet boundary conditions for both configurations. Flownex simulations for all three tests were completed. The O_2 calculated by Flownex, for both configurations were then compared to the velocity-weighted average O_2 of the duct determined from the traverse tests. The error between Flownex and the duct average was determined for both designs, for all three sets of tests and are illustrated in Fig. 28.

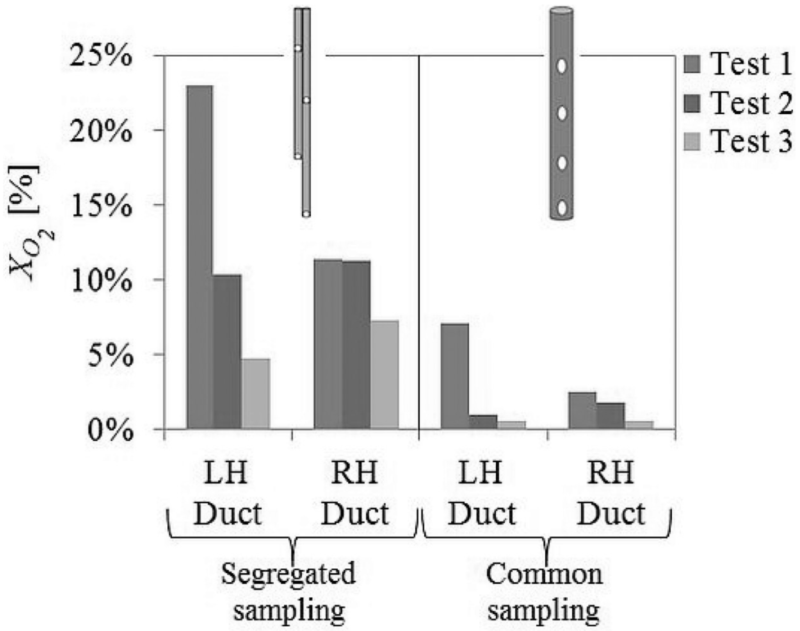


Fig. 28. Error difference between Flownex calculated O_2 and the test measured duct average O_2 (%)

Fig. 28 illustrates that for the same duct conditions, the percentage error between the average O_2 measured across the each duct and the O_2 calculated by Flownex is constantly higher for the segregated sampling configuration when compared to the common sampling pipe design, with 23% and 11.4% for the segregated sampling system, Test '1", left and right duct respectively and 7.1% and 2.5% for the common sampling system, Test '1', left and right duct respectively. The percentage error difference for the segregated sampling design reduces from Test '1' to Test '3', with 23% and 11.4% for Test '1' down to 10.4% and 11.3% for Test '2' and further reduces to 4.8% and 7.3% for Test '3'. This confirms the results from the two-point study. It also confirms that the duct flow distribution has a significant impact on the O_2 measurement. In section 4.1 we have seen that the duct flow distribution improved from Test '1' to Test '3', which resulted in the improvement in the percentage error difference.

The significant errors (23% and 11.4%) incurred with the segregated sampling are due to the variance in the sample of flue gas extracted through each port. This is due to the relatively small sampling pipe diameter (10mm) which produces a different flow resistance for each pipe length. Smaller errors (7.1% and 2.5%) are introduced with the common sampling design as a result of the lower flow resistance produced through a pipe with a larger diameter (50 mm). As a result, a far more equal sample of flue gas is extracted through each port. The study has indicated that the common sampling configuration provides a better approximation of the average O_2 of the duct when compared to the segregated sampling system configuration. The sampling errors incurred with the current system installed at Power Station A can be significantly reduced by adopting the common sampling system design.

5. CONCLUSIONS AND RECOMMENDATIONS

- The traverse test measurements clearly indicate that there is air ingress along the side walls of the boiler system.
- It is imperative to have an airtight multipoint measurement system to ensure that Power Station A's boilers are operated efficiently as the air leaks identified around the purge points exacerbated the error between the traverse test measured O_2 and the online recorded O_2.
- The systematic analysis carried out with the two-point systems showed the sensitivity of the segregated and common system to dimensional and flow parameters.
- Based on the Power Station A's flue gas O_2 and velocity distribution, the parameter study on the segregated sampling design indicated that errors up to 23% are incurred, which is independent of the error contributed by the air leaks identified around the purge points.
- The parameter study also showed that the common sampling pipe design produces smaller errors, between 0.6% and 7.1%, which is also shown by comparing both systems to traverse test measurements at Power Station A.
- It is recommended that Power Station A implements the common sampling pipe design to obtain a better approximation of the true average O_2 of the duct to improve the measurement of the boiler flue gas O_2 concentration.

SYMBOLS

Symbols

CO	carbon monoxide, ppm
D	pipe diameter, mm
d	extraction port diameter, mm
K	duct flow distribution factor, (m/s)/(m/s)
L	pipe length, mm
$\dot{m}$	mass flow, kg/s
MW	mega watt, MJ/s
u	velocity, m/s
$\bar{x}$	average concentration, %
X	error difference, %

Greek symbols

λ	excess air, %

Subscripts

m	measured
O_2	oxygen
r	recorded
1, 2	pipe 1, pipe 2

Abbreviations

ISO	International Organization for Standardization
LH	Left hand
RH	Right hand

REFERENCES

Bhatt S.M., 2007. Effect of air ingress on the energy performance of coal fired thermal power plants, *Energy Convers. Manage.*, 48, 2150–2160. DOI: 10.1016/j.enconman.2006.12.023.

British Standard, 2013. BS EN ISO 16911-1:2013: *Stationary source emissions. Manual and automatic determination of velocity and volume flow rate in ducts. Manual reference method*, Published: 31 March 2013.

ESKOM, 2013. *Company information.* Available at: http://www.eskom.co.za/OurCompany/CompanyInformation/Pages/Company_Information.aspx .

ESKOM, 2012. *Fossil fuel firing regulations*. Regulation edn, Coal Fired Power Stations, ESKOM, Generation Division.

Innami Y., Murata, A., Yuki Y., Yoshimura E., 2011. Real-time CO measurement in a coal fired boiler with a TDLS analyser. *SICE Annual Conference 2011*, Yokogawa Electric Corporation, Tokyo, Japan, September 13–18, p. 92.

Molloy R.C., 1981. Microprocessor based combustion monitoring and control systems utilizing in-situ opacity, oxygen, and CO measurement. *The Third Industrial Energy Technology Conference Houston Dynatron Inc*., Wallingford, Connecticut, April 26–29, p. 333.

Scott J., Dennis B., 2010. *Practical issues of combustion oxygen measurement specifically related to NOx emissions*, Yokogawa Corporation of America, USA. Paper no: PWR2004-52045. Available at: www.yokogawa.com/us/technical-library/white-papers/practical-issues-in-combustion-o2-measurement-specifically-related-to-nox-emissions.htm

Van Wyk D.C., 2007. *Feasibility Study Report*. ESKOM, Matimba Power Station, Limpopo, RSA.

Yokogawa 2008, *Carbon monoxide measurement in coal-fired power boilers*. Yokogawa Corporation of America, USA. Available at: http://cdn2.us.yokogawa.com/TDLS_A_001.pdf.

Received 16 March 2015
Received in revised form 01 July 2015
Accepted 05 October 2015