Investigation of Cracks and Damages at the Bends of Soot Blower tubes

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Abstract

At the SASOL power generating station in Secunda, South Africa, the ash producing fuels used to fire the boilers cause build-up of combustion by-products on the surfaces of the boiler, including soot, ash and slag on the walls of the economisers, re-heaters and super-heaters. The need to clean up those by-products is identified and the equipment used to reduce this effect at SASOL is the soot blower. During the operation of the equipment, it is realized that the tubes of the soot blowers develop cracks that hinders their function. This paper investigates the causes of cracks and damages at the bends of Soot Blower tubes. A Computational Fluid Dynamics model of the lance tube is presented in this the paper. The section of the tube where the steam and flue gases pass were modelled to obtain detailed distributions. The results of temperature and pressure distributions on the lance tube body is presented. Actual temperature and pressure ranges of the boiler were kept at 800-1000 degrees Celsius and 800-1000 kPa respectively. The results revealed high temperature at the tip of the lance tube near the nozzle. The intrusion of flue gases results in harmful chemical reactions that cause corrosion to the tubes.

Keywords

Soot Blower; Ansys CFX® modelling; Heat Transfer, Flue Gases; SASOL.

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1. Introduction

In the SASOL boilers, water is converted into high pressure and temperature steam with the help of heat energy derived from chemical energy of burning coal. Electricity is produced by the spinning generator caused by the flow of steam to the turbine. This steam is used for various purposes such as power generation and other processes. The same steam is recirculated back to water and returned to the boiler to restart the heating process. The components of the soot blower must be optimised to improve the reliability of the system. The components include lance tubes, feed tube, nozzle, poppet valve, just to name a few. This paper aims to identify the factors that affect the life of these critical components of the soot blower. These components should be made of a strong material since they operate in an environment of high temperatures and pressures. The lance tubes at the plant are made of heat resistant steel. This paper simulates static structural, thermal stress and mechanical stress on the body of the tubes to optimise the performance of the system inside the boiler. During the operation of the boiler, the tubes in the soot blowers experience tremendous pressures and high temperatures so a careful consideration must be made on the type of material the tubes are made of (Chauhan, 2017). The temperature of the boiler serves as a constraint to the design of the lance tube of the soot blower in a sense that the material chosen should be able to withstand the temperatures and not fail due to temperature changes. The type of cleaning medium, its pH and its viscosity could also constrain the type of material to be chosen for the design. These constraints should be carefully analysed to ensure that the design functions optimally. The purpose of this investigation is to identify the causes of cracks and damages visible at the bends of the lance tubes of the soot blowers at SASOL Synfuel Power Plant in Secunda (Shandu, 2021; Shandu, et. al 2019l Shandu et al, 2021).

The mechanism used to clean these boiler tubes is the soot blowing mechanism, using a type called the long rotary soot blowers. Soot blowing is essential to be performed at sufficiently frequent intervals. As much as Soot blowing is essential, it must be noted that the unnecessary use of soot blowers wastes steam. The objective of soot blowing should be to remove deposits from the boiler tube banks and the super-heater. It should be on a selected cycle, which is based on the running observations of the plant (Synfuels, 2002). Figure 1 shows the soot that has accumulated on the bends of the boiler tubes. Due to the need to keep these tubes clean of deposits, soot blowers are employed. To remove the soot, the following procedure is carefully followed for efficient cleaning:

- Ensuring that all the soot and grit hoppers are clear.
- Soot blower steam range and control is automatically warmed-up.
- Drain valves are opened on steam lines.
- Opening the Soot Blower main isolating valve.
- Piping is allowed to warm-up until the warmed up air is condensed, steam is cleared from all the lines.
- The (HV9041) is opened wide.
- Changing down to manual and control of the combustion chamber draught.
- Run the combustion chamber at a draught approximately 60 Pa above the normal conditions.
- Blowing is commenced on selected blowers, starting by the sections of the super-heaters then to the boiler convection surface blowers.
- The combustion control should not be left on automatic if the cleaning of the tube banks is in operation.

Figure 1: Soot deposits at the bends of boiler coils

Table 1 summarises the typical failures that occur in the Soot Blower system, their causes and the type of disturbance it causes the whole boiler operation. Sasol Synfuels should consult the maintenance manual to rectify the errors that result from these causes listed in Table 1, (Shandu, 2020; Synfuel, 2002).

Table 1: Analysis of Soot Blower System Failures

Component	Function	Failure Mode	Cause of failure
Nozzle	Transfer steam to boiler tubes	Overheating (Long-term)	Improper material
Lance Tube	Transfer steam to boiler tubes	Overheating (Short-term)	Insufficient steam jet pressure/Flue Gas Intrusion
Poppet Valve	Start/Stop soot blower	Steam leakage	Improper Material/Worn out
Feed Tube	Transfer steam from poppet valve to lance tube	Overheating	Material fatigue

The boiler efficiency is highly affected by the temperature gained by the water in the tubes. A clean boiler has a relatively high temperature as compared to a fouled boiler. A high temperature is associated with the high heat transfer and high heat flux. On the other hand, a fouled boiler reduces the temperature almost to half of its magnitude, this is due to the soot absorbing the heat produced in the boiler. Hence, the performance of the boiler is reduced (Zhanhua, et al., 2010). The aim of this paper s to simulate the soot blower tubes in order to predict the cause of damages and cracks. It is observed that the intrusion of flue gases causes a lot of soot blower tube fatigue. A high concentration of elements like Na, O, Si and S was observed. The harmful chemical reactions result in chemicals like Fe_2O_3 and Fe_3O_4.

2. Materials and Methods

2.1 Materials

The methods that were used to arrive at the solution are presented in this section. The lance tube that the study is based on has different materials at each section. The reason for this is that these sections are subjected to different conditions of the boiler. The rear-end of the tube is not experiencing high temperatures while the far-end, at the tip of the tube i.e. nozzle section, the temperatures are high. A careful consideration on the type of material used at these respective sections is of importance.

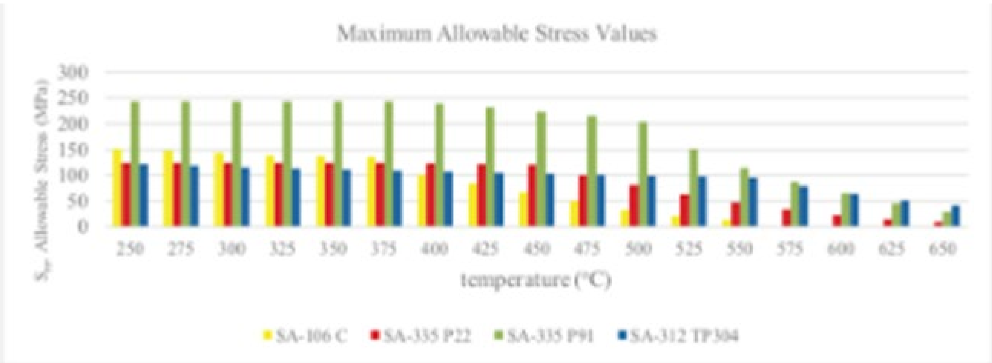


Figure 2: Heat-resistant material's Maximum Allowable Stress (Zhanhua, et al., 2010)

Sasol Synfuels power plant uses boiler components from an international supplier, Babcock and Wilcox (Synfuels, 2002). The manufacturer advises that their components are High alloy heat resistant type of materials. The reliability of the lance tubes, or any boiler component for that matter, is graded by the quality of its welded joints (BABCOCK & WILCOX CONTRACTOR, 1994). Figure 2 show that the maximum allowable stress of different heat-resistant materials decreases as the temperature increases.

Table 2: Material selection

Components	Material	Reason
Feed Tube	Stainless Steel	High strength
Lance Tube	Titanium Steel Alloy	High strength to support the tube as it is suspended inside the boiler.
Nozzle	Stainless Steel	Subjected to hot flue gas longer than all the components so high strength is essential.
Poppet Valve	Cast Iron Alloy	Can withstand high temperatures.

Table 2 shows the material of the investigated lance tube and the reason why the chosen material was the best solution to ensure reliability of the components. Different analysis approach was helpful in conducting a detailed analysis of temperature and pressure distributions across the tubes.

2.2 Methods

2.2.2 FEA Analysis of Lance Tube

The actual dimensions of the lance tube as obtained from Sasol were used to draw a 3D AutoCad Inventor professional model to simulate the fluid flow on (Zhanhua, 2010). The volume where the fluid flows was extracted and the boundary conditions and all the parameters affecting the flow of steam were integrated on the software. The software used to do the analysis was Ansys CFX®.

Table 3: Soot Blower Parameters

Property	Dimension
Maximum insertion length (mm)	9,750.00
Travel of blown steam (mm)	10,000
Speed (m/s)	0.03
Operating time (min)	10
Blowing time (min)	9,45
Flow of steam (kg/s)	150
Continuous Blowdown (kg/s)	15
Steam pressure (MPa)	4.25
Steam consumption (kg/s)	1.4
Inlet temperature (steam jet) (K)	623

The simulations were generated to determine the most vulnerable parts of the lance tube by computing the heat transfer, inputting all the boiler operational conditions. The material of the lance tube was the specified one from the manufacturer. The mesh was generated using tetrahedral type that is of fine quality, Figures 3 and 4. The physics preference for the sake of simulating the fluid flow was chosen as CFD and the solver as CFX. The Inflation was set to create a fine mesh on the body of the tube, also changing to first layer thickness.

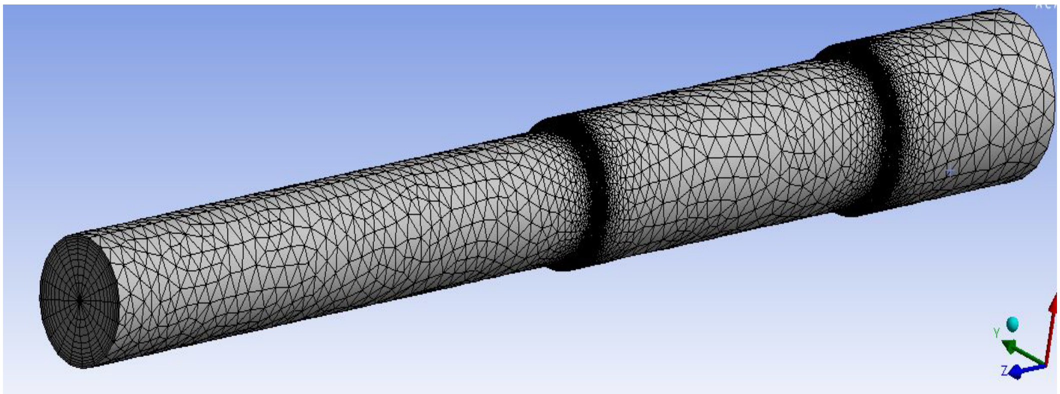


Figure 3: Tetrahedral Mesh on the tube from Ansys

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	CFX
Element Order	Linear
Element Size	9.e-002 m
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	9.e-002 m
Mesh Defeaturing	Yes
Defeature Size	Default (4.5e-004 m)
Capture Curvature	Yes
Curvature Min Size	Default (9.e-004 m)
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	0.97136 m
Average Surface Area	2.2109e-002 m^2
Minimum Edge Length	3.1416e-003 m
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Advanced	
Statistics	
Nodes	134602
Elements	299163

Figure 4: Details of Mesh from Ansys

3. Results

3.1. The Need for Soot Blowers

With the help of the actual data obtained from Sasol (Shandu, 2020; Synfuels, 2002), calculations of heat loss of the boiler were performed. One of the reasons why Soot blowers are employed at the Power plants is to maintain the efficiency of operation. The efficiency is hindered by a number of factors that vary with the conditions of the working environment and the quality of coal that is being used. Table 4 shows the instrumental data for the boiler, classifying it into heat output data and heat input data. From direct methods, the efficiency of the boiler can be obtained.

Table 4: Instrumental Data of the Boiler

Heat output data	
Type of Boiler	Coal Fired Boiler
Quantity of generated steam(kg/hr)	1685000
Steam Pressure(MPa)	4.25
Enthalpy of Steam (Dry and saturated at 10 kg/cm^2)	3478.32
Feed water enthalpy(kJ/kg)	1193.73
Feed water temperature(°C)	265
Heat input data	
Quantity of coal consumed(kg/hr)	290000
Grand calorific value of coal(Kj/kg)	14568.9

$$\text{Efficiency of the Boiler}(\eta) = \frac{\mathrm{Q(H-h)}}{\mathrm{q{\times}GCVofCoal}} \times 100 \tag{1}$$

Where: Q = Quantity of generated steam(kg/hr)
q = Quantity of fuel consumed in an hour
GCV = Gross Calorific Value of Fuel
H = Enthalpy of steam
h = Enthalpy of feed water

$$\therefore \eta = \frac{Q(H-h)}{q \times GCVofCoal} \times 100$$

$$= \frac{1685000 \times (3478.32 - 1193.73)}{14568.9 \times 290000} \times 100$$

$$= 91\%$$

From the indirect methods, the boiler efficiency with and without soot blower is determined. The heat losses include:

1. Percentage heat loss as a result of Dry Flue Gas.
2. Loss of heat due to H2 Evaporation in water.
3. Loss of heat due to the presence of moisture in fuel/
4. Loss of fuel due to the moisture in air.
5. Heat loss due to incomplete combustion.
6. Heat loss as a result of convection and radiation.
7. Heat loss due to unburnt ash.
8. Unburnt fuel in the bottom ash.

Table 5: Detailed representation of all the percentage heat losses for each boiler

	$Loss_1$	$Loss_2$	$Loss_3$	$Loss_4$	$Loss_5$	$Loss_6$	$Loss_7$	$Loss_8$
No Soot Blower	10.7	4.8	1.78	0.45	4.4	0.55	0.4678	4.14
With Soot Blower	6.97	4.68	1.7	0.337	2.9	0.47	0.4678	4.14

Table 5 tabulates the different heat losses for the different boiler cases and the information was used to plot Figure 5.

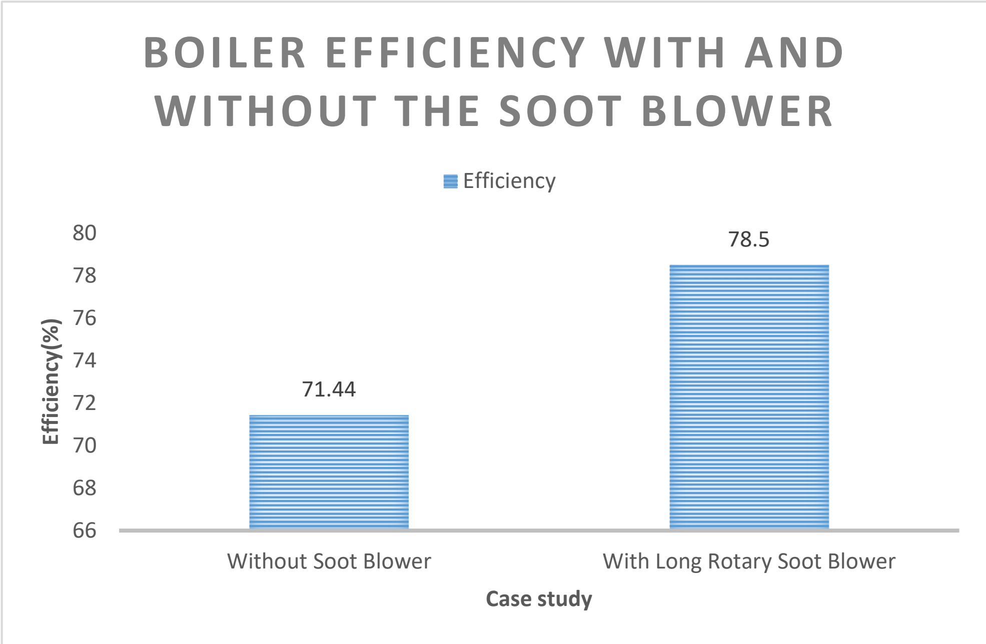


Figure 5: Boiler efficiency comparison.

From the bar graph of Figure 5 it is clear that the soot blower is of importance to the boiler. The efficiency declines by more than 7%, when there is no soot blower that operates in the boiler. This is source of concern for such a huge power plant.

3.2. Related Calculations

The operating temperature inside the tube can be estimated from the parameters of Larson-Miller (Nugroho & Pramono, 2018).

The formula for scale thickness as;

$$\log\left(\frac{X}{0.0254}\right) = 0.00022P - 7.25$$

Where: X = Scale thickness (mm)
P = Larson Miller parameter

The Larson-Miller parameter can be further modified to get the following equation;

$$P = \left(\frac{9}{5}T + 492\right)(C + \log t)$$

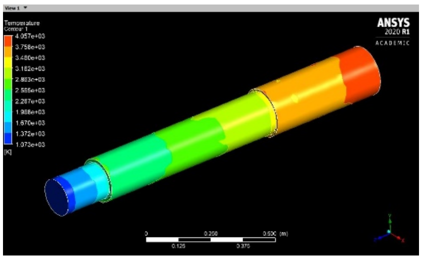
Where: T = Temperature ($°C$)
t = Service time (hours)
C = constant = 20

The Hoop Stress that develops in the tube can be estimated by the equation below

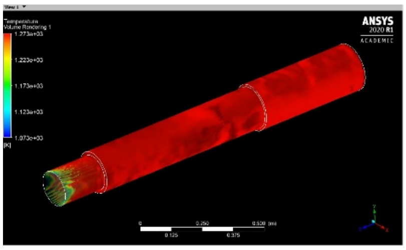
$$\sigma_h = p\left(\frac{r + \frac{h}{2}}{h}\right)$$

Where: p = operational internal pressure
r = inner radius
h = wall thickness of the tube

The parameters values of these equations and Table 4 were put on the software for simulation of the tubes in order to analyse what the effects of high temperatures and pressure have on the surface of the lance tube. Following the FEA the vulnerable areas of the tube were revealed.



(a)



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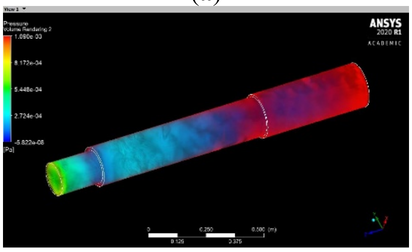

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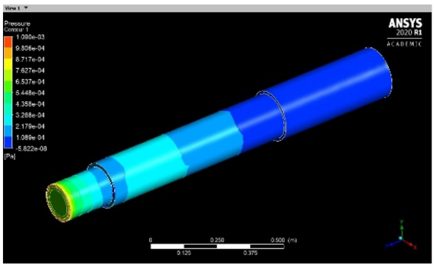

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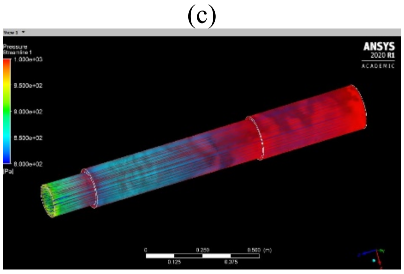
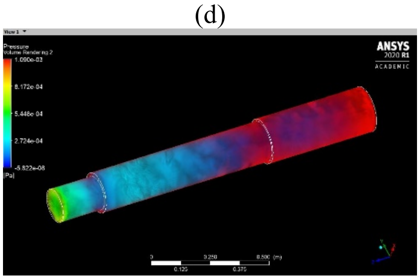


(e)



(f)

Figure 6: Simulations

Figure 6. (**a**) Temperature contour; (**b**) Temperature Volume rendering; (c)Temperature Streamlines; (d) Pressure Contour; (e) Pressure Streamlines; (f) Pressure Volume rendering.

4. Discussion

Figure 6(a) shows the result of temperature simulation and its effect on the critical parts of the tubes, the maximum temperature is at the nozzle section. That tells us that the cracks are likely to occur at the nozzle tip. Figure 6(b) show the heat transfer of the tube as it is inside the boiler, only the part that is not exposed to the inside of the boiler shows the minimum temperature range. It is clear that if the tube can remain inside the boiler longer than expected, it is likely to fail and develop cracks. Figure 6(c) shows how the temperature increases when the tube is in operation and how it decreases as it retracts from the boiler. The pressure contour, Figure 6(d), shows that the tube is experiencing pressure even when it is idling. Figure 6(e) shows the streamlines of the pressure distribution on the pipe, indicating that the most vulnerable section to the boiler pressure is the nozzle tip, that is the steam that is blown has to pass there so as to ease that pressure.
From the equations in section 3.2., since the wall thickness of the tube varies at different sections, the temperature distribution inside the tube will be constant. Some parts of the tube, especially the far-end by the nozzle section, will experience high temperature distributions and will be the one likely to develop cracks since the hoop stresses at that point will be higher (Shandu et al, 2021). During the Soot Blower operation, the lance tube stands outside of the boiler and periodically enters. In the periods that it idles inside the boiler, the tubes adapts to the ambient temperature of the boiler house at approximately 52°C. The corrosives i.e. water vapor and sulphur dioxides can be blown into the lance tube from the furnace and eventually forming acidic sodium bisulfate ($NaHSO_4$) as represented here (Fatah, et al., 2020):

$$SO_2 + H_2O \leftrightarrow H^+ + HSO_3^-$$

$$HSO_3^- \leftrightarrow H^+ + SO_3^{2-}$$

$$HSO_3^- + \frac{1}{2}O_2 \rightarrow SO_4^{2-} + H^+$$

$$SO_3^{2-} + \frac{1}{2}O_2 \rightarrow SO_4^{2-}$$

$$SO_2 + \frac{1}{2}O_2 + H_2O + Na_2SO_4 \rightarrow 2NaHSO_4$$

Inside the furnace, the $\mathrm{NaHSO_4}$ melts as the temperature of the lance tube wall increases (Shandu, et al., 2018). The molten $\mathrm{NaHSO_4}$ is a corrosive liquid that damages the alloys of stainless steel. As the temperature increases, the sensitization of the tube begins, and the cracks starts to form. A film density is visible on the steel surface. It can be determined from the chemical reactions that the film is a reaction between the stainless steel and water vapour.

$$Fe + 3H_2O \rightarrow Fe(OH)_3 + {}^3/_2\,H_2$$

$$2Fe + 3H_2O \rightarrow Fe_2O_3 + 3H_2O$$

$$4Fe_2O_3 + Fe^{2+} + 2e^- \rightarrow 3Fe_3O_4$$

The pits develop on the areas with low density by causing diffusion that results to localized corrosion (Shandu, 2020).

5. Conclusions

From the findings, it can be concluded that the cracks are caused not only by one factor but also by a number of factors. One of the factors that contribute to the cracks on the lance tubes, as investigated, is the exposure to high temperatures. This leads to different kinds of stresses i.e. thermal stresses and hoop stresses. The pits that form as a result of a chemical reaction between the stainless steel and the water vapour are causing corrosion on the tubes. The intrusion of flue gases via the air-purge system causes damage to the lance tubes when the water vapour reacts with the material of the tubes.

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