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Effect of Diameter on Steam Pressure Soot Blower to Eliminate Low Potential Slagging and Fouling

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ABSTRACT

The combustion process in pulverized coal boilers utilizes coal fuel, which produces ash and heat. Ash from combustion process will be deposited and adhere to pipes, known as slagging and fouling. Cleaning of slagging and fouling is done using a soot blower by flowing pressurized fluid to generate a jet nozzle force, which can remove the slagging and fouling adhering to the pipes in the superheater. Based on testing of parameters, ash fusion temperature is 1415.42 °C, and silica ratio is 79.55%, indicating a low potential for slagging. For fouling testing yielded an index of 0.089, indicating a low potential for fouling. The existing retractable soot blower operates using superheated steam with a pressure of 70-75 bar. In the design of low-pressure soot blower, flow is derived from intermediate pressure turbine by modifying feed tube, lance tube, and soot blower nozzle. The design results in a feed tube diameter of 101.65 mm, a lance tube diameter of 114.3 mm, an inlet nozzle diameter of 21.1 mm, a throat nozzle diameter of 13.97 mm, and an outlet nozzle diameter of 41.02 mm, with a Mach number output of 2.09 and a total jet force of 2023.9 N.

INTRODUCTION

The combustion process in boiler requires coal fuel of a certain quality to get complete combustion. Coal quality is determined by several parameters including moisture, volatile matter, ash, fixed carbon, and heating value [1]. Coal parameters can be obtained from several analyses carried out on coal including proximate analysis, ultimate analysis, ash analysis, and ash fusion temperature [2].

In the process of burning coal will produce ash and heat. Ash is remaining powder residue in form of mineral matter after combustion process [3]. Ash from coal combustion process in steam generator unit produces two types of ash, namely fly ash and bottom ash [4]. Ash has different melting temperatures, which can be determined through ash fusion temperature analysis. If melting temperature of ash is lower than the combustion temperature, then when ash passes through the pipes of the combustion chamber walls it causes condensation and causes ash to stick, which is known as slagging and fouling. Slagging and fouling can have a major impact on boiler operations, such as heat transfer problems, decreased boiler efficiency, pipe blockages, and pipe damage due to clinker release [5]. The phenomenon of slagging and fouling in boilers can be overcome by operating a soot blower.

Soot blower is a tool used to clean slag attached to boiler pipes which is formed because of combustion process [6]. Soot blower is operated under on load cleaning conditions using superheat steam from the superheater. The soot blowing process uses superheated steam with a high pressure of 70–75 bar. Then the superheat steam will pass through pressure reducing stations to lower the pressure to 11.5 – 12 bar.

The novelty of soot blower modification is carried out by changing the components of the feed tube, lance tube and nozzle. This low-pressure soot blower concept does not use pressure reducing stations because it takes steam from the extraction turbine at a lower pressure.

METHODS

Data Collection

Data was taken from TMCR (Turbine Maximum Continuous Rate) conditions to determine turbine extraction conditions. The selection of turbine extraction is based on a soot blower that works at a steam pressure originating close to its working pressure.

Determination of Design Criteria

The following are the soot blower design criteria:

1. Fluid flow in nozzle is supersonic flow with mach number 1.2 <Ma< 3.0 [7].
2. Total output jet force is greater than the deposit force [8].

Slagging and Fouling Potential

In slagging parameter to determine level of potency using calculations based on ash fusion temperature, iron calcium ratio, and silica ratio [9]. For fouling parameters based on Na_2O content and acid base ratio [10].

Ash fusion temperature equation can be rewritten as:

$$AFT\ (^oC) = \frac{(4\ x\ I_{ADT}) + HT}{5} \quad (1)$$

Table 1 *Ash Fusion Temperature Potential Parameters [11]*

Indeks	Potensi
1343<slag	Low
1232<slag≤1343	Medium
1149<slag≤1232	High
Slag≤1149	Very High

Silica potential equation can be rewritten as:

$$\%Silika = \frac{\%SiO_2}{\%(SiO_2 + Fe_2O_3 + CaO + MgO)} \quad (2)$$

Table 2 Silica *Potential* Parameters *[12]*

Indeks	Potensi
72 < slag < 80	low
65 < slag ≤ 72	Medium – high
50 < slag ≤ 65	Very high

Fouling factor equation can be rewritten as:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O}{SiO_2 + Al_2O_3 + TiO_2} \quad (3)$$

$$Rf = \frac{B}{A}\ x\ \%Na_2O \quad (4)$$

Table 3 *Fouling Factor potential* Parameters *[14]*

Indeks	Potensi
≤ 0.2 ff	low
0.2 < ff ≤ 0.5	medium
0.5 < ff ≤ 1	High
> 1 ff	Very High

Feed Tube and Lance Tube iterations

The design criteria are in pre-input nozzle, so it is necessary to do a backwards calculation before the input nozzle, namely in feed tube and lance tube sections with iteration method.

$$\Delta Ptotal = \Delta Pfeed\ tube + \Delta Plance\ tube \quad (5)$$

Nozzle Size Determination

Calculation of inlet nozzle diameter, throat nozzle diameter and outlet nozzle diameter can be carried out after determining the design parameters of low-pressure soot blower, namely jet force and mach number [14]. To calculate the diameter of the nozzle outlet is based on the mach number that has been adjusted to the design criteria. The spray nozzle angle is a reference for calculating the throat nozzle diameter [15] . To calculate the diameter of the inlet nozzle, it is necessary to consider the cross-sectional area of the inlet by considering the inlet nozzle pressure and nozzle outlet pressure.

$$\Delta P_{tube} = f\frac{8\ x\ L_{LT} x \dot{m}_{fluida}^2}{\pi^2\ x\ D_{in}^5\ x\ \rho_{fluida}} \quad (6)$$

$$\frac{P_{nozzle}}{P_{exit}} = \left(1 + \frac{k-1}{2}M^2\right)^{\frac{k}{k-1}} \quad (7)$$

$$\frac{F_{jet}}{\frac{1}{4}\pi D_{exit}^2} = \frac{F_{nozzle}}{\left(1+\frac{k-1}{2}Ma^2\right)^{\frac{k}{k-1}}}\left(\frac{k+1}{2}Ma^2\right)^{\frac{k}{k-1}}\left(\frac{k+1}{2Ma^2-(k-1)}\right)^{\frac{1}{k-1}} \quad (8)$$

$$D_{throat} = D_{exit} - 2\ln\tan\left(\psi_{deviasi}\right) \quad (9)$$

Soot blower validation using Ansys Fluent R22

The next step is validation by conducting a simulation on the ANSYS fluent software to find out the Mach number on the soot blower [16]. The steps for validating and analyzing the design results in a simulation using Ansys Fluent are as follows:

1. Setting up the Simulation Model
2. Fluid Flow Simulation
3. Data visualization

RESULTS AND DISCUSSION

Slagging and Fouling Potential

Slagging and fouling affect shear stress deposit value. When there is an increase in the accumulation of deposits on the surface of the pipe, it will affect the shear stress deposit value. To determine the shear stress value of a deposit, it is necessary to know the potential level of slagging and fouling.

The ash fusion temperature test parameter aims to determine the temperature required for the coal ash melting process [17].

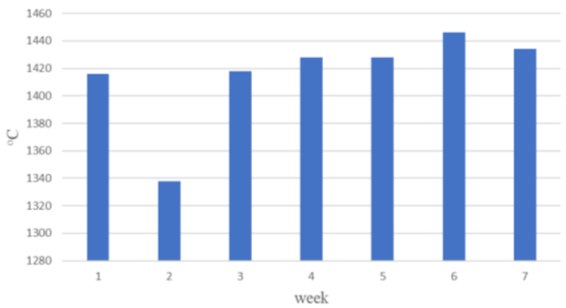

Figure 1. Ash Fusion Temperature

Based on results of proximate analysis data processing. Average ash fusion temperature is 1415.42 oC which is included in the low category. To find out indication level of ash fusion temperature, refer to references [10] shows the range for the low category of slag>1343°C, medium category 1232°C < slag ≤1343 °C, for high category 1149 °C < slag ≤ 1232 °C, and for very high category slag ≤ 1149 °C. The higher the ash fusion temperature, the more difficult it is for the coal ash to melt and stick to the combustion chamber wall pipe, so the potential for slagging will be lower.

The silica ratio test parameter represents the mass percent of SiO_2 in the comparison of the composition of coal to the content of Fe_2O_3, CaO and MgO [18].

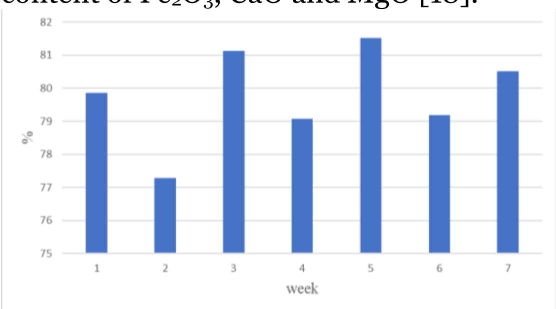

Figure 2. Rasio Silika

The results of data for the content of SiO_2, Fe_2O_3, CaO and MgO produce an average silica ratio of 79.55% which is included in the low category. The higher the iron-calcium ratio in coal ash, the lower the potential for slagging. This is because the low iron content in coal ash reacts with calcium oxide (CaO) in the ash and forms calcium ferrite ($CaO{\cdot}Fe_2O_3$) which has a high melting point and a low tendency to stick to the boiler walls.

Parameter of fouling factor is influenced by the content of potassium, sodium, and alkali metals. The determination of the characteristics of fouling factor uses the parameters of acid-base ratio and percentage of Na_2O [19].

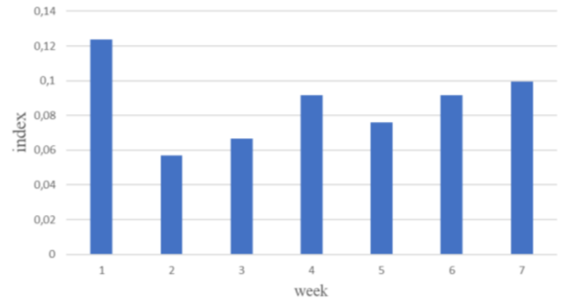

Figure 3. *Fouling Factor*

The results of data processing of acid base ratio and percentage of Na_2 produce an average fouling factor of 0.089 which is included in the low category. The range of fouling factor for the low category is <0.2, the medium category is 0.2 <ff ≤ 0.5, the high category is 0.5<ff ≤1.0. The element that has the most influence on fouling is alkaline material, especially the Na_2O content. If there is a lot of coal ash, then there are also a lot of alkaline elements in the ash, plus a high Na_2O content, then fouling will easily occur. High Na_2O levels tend to encourage fouling. Fouling can cause a decrease in the rate of heat transfer between flue gas and steam in the superheater.

Based on results of potential slagging and fouling potential parameter data. The slagging and fouling potential index can be obtained in the low category as shown in **Table 3** and **Table 4**.

Table 4. Slagging Potency

Parameter	Index	Potency
AFT (°C)	1415.4	low
Ratio silica (%)	79.55	low

Table 5. Fouling Potency

Parameter	Index	Potency
Fouling factor (Rf)	0.089	low

Shear stress deposit value for the slagging and low fouling category is 10 kN/m² [20]. In soot blower operation, the nozzle must be able to generate a greater force to clean deposits attached to the surface of the pipe.

To obtain optimal deposit force, feed tube diameter and lance tube diameter were tested. The results of feed tube and lance tube design data serve as a reference for the appropriate nozzle design criteria for cleaning slagging and fouling.

Soot blower Feed Tube Testing

Soot blower feed tube circulates steam generated from boiler to soot blower so that steam can reach the surface of superheater pipe to clean deposits adhering to its surface. Feed tube testing was carried out with variations in diameter. To obtain an optimal design requires manual calculations with the ANSYS Fluent iteration and validation method.

In designing soot blower feed tube, taking the lowest pressure drop is prioritized to ensure that the steam flowing out of feed tube has optimal pressure.

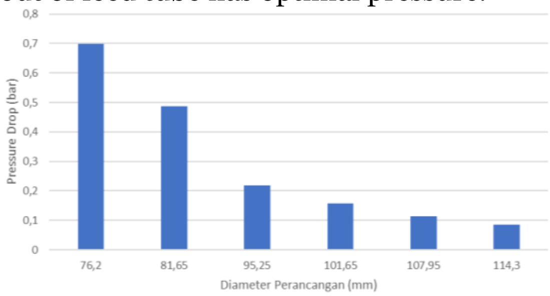

Figure 4. Pressure Drop Feed Tube Profile Based on Iteration Method

Pressure drop in pipe is caused by friction between fluid and inner surface of pipe and changes in pipe size which cause acceleration or deceleration of fluid flow. In designing a feed tube with a diameter of 101.65 mm it will produce a friction factor of 0.0162. Based on the results of data processing by changing the diameter variation, the larger the diameter of the feed tube will result in a lower friction factor.

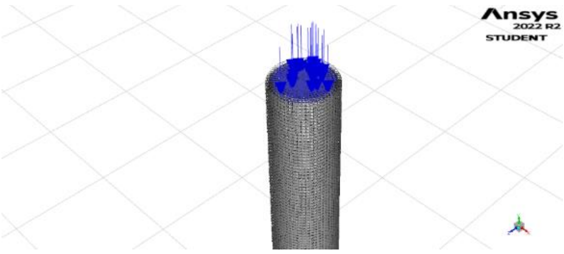

Figure 5. Feed Tube Input flow

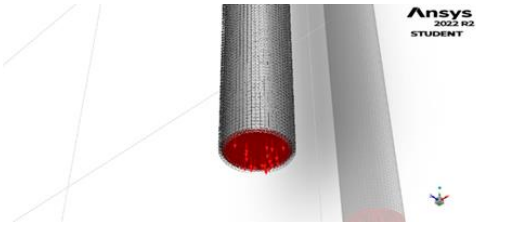

Figure 6. Feed Tube Output flow

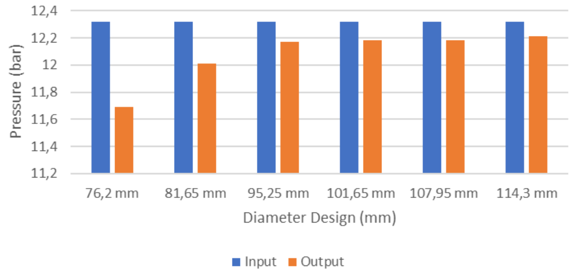

Figure 7. Comparison of Feed Tube Input and Output Pressure Parameters Based on ANSYS Fluent Validation

Based on **Figure 7** it shows that with a diameter of 76.2 mm it produces a pressure drop of 0.63 bar. Pressure drop will be sloping in the last 3 data, specifically 101.65 mm, 107.95 mm and 114.3 mm which are below 0.08 bar.

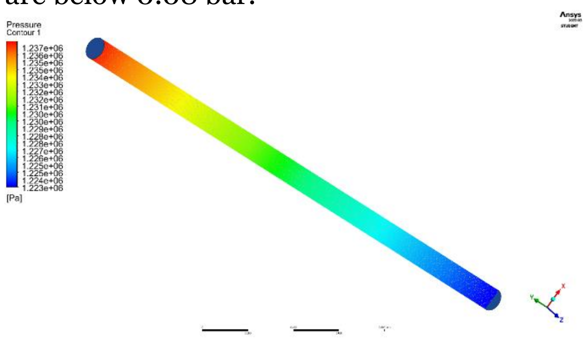

Figure 8. Fluid Computation Profile for Pressure Parameters on Feed Tube Diameter 101.65 mm

Considering the pressure drop on feed tube, the optimal diameter is 101.65 mm. Computation of pressure in pipe flow using Ansys Fluent software, it shows pressure distribution in soot blower feed tube. The maximum pressure is 1.237e+6 Pa in the feed tube input area and the minimum pressure is 1.223e+6 Pa. In pipe flow, as the diameter of the pipe increases, the pressure drop decreases. This is due to larger pipe, the pipe cross-sectional area available for fluid flow will be greater, so that fluid flow will have a lower velocity. When the pipe diameter is larger, the surface area in contact with the fluid increases. As a result, the fluid has a larger area to flow along, reducing the velocity and decreasing the frictional force between the fluid and the pipe wall. This leads to lower frictional losses and a decrease in the pressure drop along the pipe.

Testing of Lance Tube Soot blower

Soot blower lance tube circulates steam from feed tube to the soot blower nozzle. Lance tube test was carried out with variations in tube diameter. To obtain an optimal design requires manual calculations with the ANSYS Fluent iteration and validation method.

Testing of lance tube soot blower refers to a low pressure drop parameter to ensure optimal steam pressure flow.

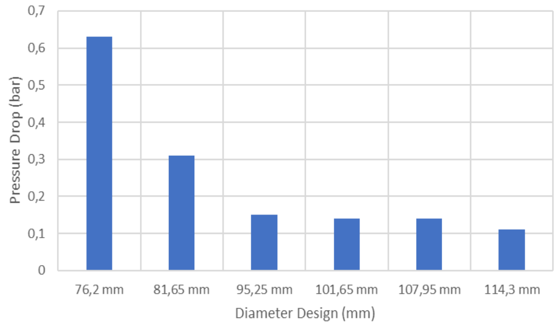

Figure 9. Pressure Drop Lance Tube Based on Iteration Method

In designing lance tube soot blower, taking the lowest pressure drop is prioritized by considering slope of the pressure drop on lance tube. This aims to ensure that steam flow comes out of lance tube to nozzle has optimal pressure.

Based on **Figure 9** it shows that with a diameter of 76.2 mm it produces a pressure drop of 0.698 bar. The pressure drop will be sloping in last 3 data, specifically 101.65 mm, 107.95 mm, and 114.3 mm, already below 0.08 bar.

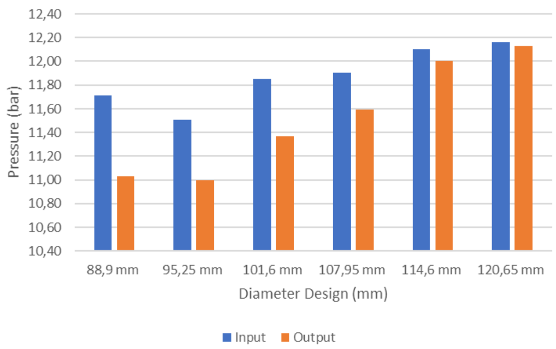

Figure 10. Comparison of Input and Output Pressure Parameters of Lance Tube Based on ANSYS Fluent Validation

The pressure drop in the pipe is caused by friction between fluid and inner surface of pipe and changes in pipe size which cause acceleration or deceleration of fluid flow. In designing a lance tube with a diameter of 114.3 mm, pressure drop will be 0.23 bar. Based on results of data processing by changing the diameter variation, it shows the larger the diameter of the feed tube, the lower the friction factor. This is because a larger diameter results in a larger cross-sectional area, which reduces the velocity of the fluid and decreases the frictional force between the fluid and the tube walls. As a result, the friction factor, which is a measure of the resistance to flow, decreases with a larger tube diameter.

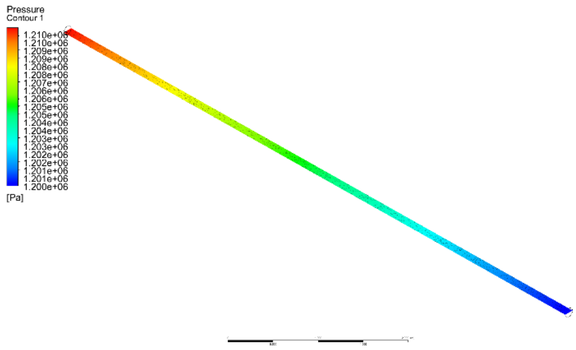

Figure 11. Fluid Computation Profile For Pressure Parameters On Lance Tube Diameter 114.6 mm

Process of calculating pressure in pipe flow using ANSYS Fluent software will be shows the pressure distribution in soot blower feed tube. By considering attention to pressure drop on feed tube, the optimal diameter is 114.6 mm. Optimal diameter selection results in a maximum pressure distribution of 1.21+6 Pa in input lance tube area and a minimum pressure of 1.20+6 Pa in output lance tube area.

Soot blower Nozzle Testing

In soot blower operation, nozzle must be able to generate a force large enough to clean deposit attached to the surface of superheater pipe. If force generated by nozzle is smaller than deposit force, the deposit will not be separated from surface of superheater pipe [21].

Table 6. Factors Affecting Deposit Force

Tube contact area	shear stress deposit	Deposit Force
0.09165 m^2	10 kN/m^2	916.5 N

Designing low pressure soot blower, it is necessary to consider jet impact pressure at nozzle exit (IP_{exit}) which can be calculated using the Rayleigh Pitot equation to describe the pressure increase in the fluid flow flowing through the nozzle and producing a jet force. The following is **table 7** of calculation results for nozzle outlet parameters.

Table 7. Output Nozzle

Nozzle input pressure (Pnozzle)	Jet impact pressure at output nozzle (IPexit)	Total Jet Force (Fjet)
174.08 psi	104.9 psig	2023.9 N

Based on **table** 7 calculation results obtained the total jet force (2023.9N) > deposit force (916.5 N). This shows that the jet in low pressure soot blower has a force large enough to clean deposits on surface. In designing a low-pressure soot blower, it is important to consider the total jet force and deposit force to ensure that soot blower is able to effectively remove surface deposits.

In designing a soot blower nozzle, calculating inlet diameter, throat diameter and outlet diameter to ensure optimal performance of the nozzle. Inlet diameter affects the amount of fluid that enters the nozzle. Throat diameter affects the velocity of the fluid in the nozzle. Outlet diameter affects shape of the jet coming out of nozzle and the jet pressure at nozzle exit.

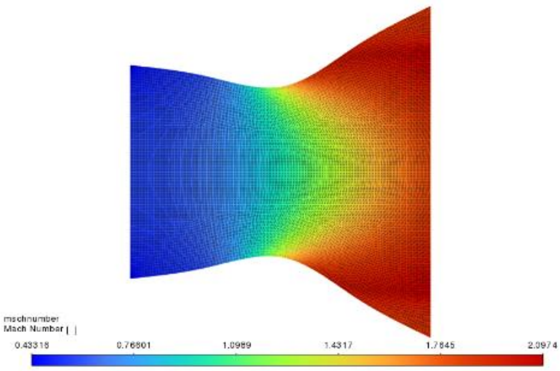

Figure 12 Nozzle Simulation Results with Mach Number Parameters

In supersonic flow, the condition of fluid flow in soot blower nozzle reaches a speed greater than speed of sound in fluid medium. Supersonic flow in soot blower can be achieved by ensuring that fluid velocity at the nozzle reaches a Mach number of 2.09 which is in accordance with design criteria. Therefore, soot blower nozzle is designed so that it can produce the supersonic flow required to clean deposits on inner surface of boiler.

CONCLUSION

Based on potential for slagging and fouling in low category, from low-pressure soot blower design, the value of feed tube diameter is 101.65 mm, lance tube is 114.3 mm, inlet nozzle diameter is 21.1 mm, throat nozzle diameter is 13.97 mm, and nozzle outlet diameter 41.02 mm. The design results produce a total jet force (2023.9 N) > deposit force (916.5 N) and output mach number of 2.09. This shows that jet in low pressure soot blower has optimal force and flow velocity to clean deposits on the pipe surface.

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REFERENCES

[1] D. Umar, Study On Chemical Characteristics Of Coal And Biomass Blend And The Tendency Of Its Ash Deposition, Bandung: INDONESIAN MINING JOURNAL, 2021.

[2] Yanqing Niu, et al, Effects of leaching and additives on the ash fusion characteristics of high-Na/Ca coal, Shaanxi: State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, 2018.

[3] R. Damayanti, Abu Batubara Dan Pemanfaatannya: Tinjauan Teknis Karakteristik Secara Kimia Dan Toksikologinya, Bandung: Puslitbang Teknologi Mineral dan Batubara, 2018.

[4] Mekkadinah, et al, Review Regulation on The Determination of Fly Ash and

Bottom Ash from Coal Fired Power Plant as Hazardous Waste in Effort to Increase Utilization in Indonesia, International Conference Earth Science & Energy, 2020.

[5] P. VERSTEEG, Monitoring kraft recovery boiler fouling using principal component analysis, Toronto: Tappi Journal, 2009.

[6] Sandeep, et al, A Literature Review on Failure of Long Retractable Soot Blower, Online: IJSRD - International Journal for Scientific Research & Development, 2017.

[7] F. White, Fluid mechanics, USA: Mc Graw Hill, 2016.

[8] Tandra, et al, Low Pressure Sootblowing Technology - The State of Development, Savannah: TAPPI PEERS Conference, 2013.

[9] J. C. Vijay, Analytical Tool For Analysing Slagging Characteristic Of High Ashcoals In Utility Boilers, India: International Journal of Mechanical Engineering and Technology (IJMET) , 2017.

[10] M. Indrayana, Potensi Kecepatan Pembentukan Slagging dan Fouling Pada Boiler PLTU Berbahan Bakar Batu Bara, Semarang: Prosiding Seminar Nasional NCIET , 2020.

[11] J. li, Effect of coal blending on ash fouling and slagging in pulverized coal fired supercritical (SC) and ultra-supercritical (UC) power plant., The university of western australia, 2016.

[12] Piotr, & Paryk, The development of a slagging and fouling predictive methodology for large scale pulverized boiler fired with coal and biomass blend., Wales: Cardiff University, 2013.

[13] Babcock, & Wilcox, Steam its generation and use 42 ed, New York: The Babcock And Wilcox Company, 2001.

[14] Tandra, et al, Energy Saving & Cost Reduction Through The Use Of 9 – 14 Bar Steam From Turbine Extraction For Sootblowing: A Case Study, Tampere: International Chemical Recovery Conference, 2014.

[15] J. Mbuyamba, Calculation And Design Of Supersonic Nozzles For Cold Gas Dynamic Spraying Using Matlab And Ansys Fluent, Johannesburg: University of Witwatersrand, 2013.

[16] S. Doroudi, ANSYS Fluent Modelling of an Underexpanded Supersonic Soot blower Jet Impinging into Recovery Boiler Tube Geometries, Toronto: Department of Mechanical and Industrial Engineering, 2015.

[17] Hui Wang, et al, Melting Characteristics of Coal Ash and Properties of Fly Ash to Understand the Slag Formation in the Shell Gasifier, ACS Publications, 2023.

[18] Wenju Shi, et al, Fly ash as a raw material for geopolymerisation - chemical composition and physical properties, IOP Conference Series: Materials Science and Engineering, 2019.

[19] Li Zhang, et al, Co-Firing Zhundong Coal with Its Gangue: Combustion Performance, Sodium Retention and Ash Fusion Behaviors, MDPI, 2022.

[20] Zenghui Zhao, et al, Compression–shear strength criterion of coal–rock combination model considering interface effect, Tunnelling and Underground Space Technology, Volume 47, Tunnelling and Underground Space Technology, 2015.

[21] F. Mettias, Measuring Soot blower Jet Forces Exerted On Deposits, Toronto: Department of Mechanical and Industrial Engineering, 2019.