# Investigation of flow inside pulverized coal (PC) pipes against coal particle size and air flow rate for a utility boiler

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**Abstract**. This study mainly focuses on investigation on effect coal particle size on flow inside pulverized coal pipes for a utility boiler. The flow that is analyzed here will be the wall shear stress. The objective of the study is to determine the effect of coal particle size and effect of air flow rate on the wall shear stress of pulverized coal pipes. The individual wall shear stress which is computed as area weighted average of the pulverized coal pipes that is studied is compared and analyzed. There are total of 28 pulverized coal pipes in the power plant that is chosen as case study. The study is divided into two parts mainly the effect of coal particle size on the wall shear stress and the other is effect of air flow rate on the wall shear stress. In both configurations the wall shear stress is computed as area weighted average. Prior to simulation the file that is used to study the wall shear stress is modified using Gambit to improve results. The individual wall shear stress of all pipes coming out of a particular mill is observed after contours are developed using CFD tool like Ansys fluent. Parameters like coal flow rate and coal velocity are set in the simulation and results are generated Based on contours and developed graph from the simulation, the effect of both configuration is studied and the range of particle size and range of air flow rate which is suitable for the optimum operation of boiler is suggested.

**Keywords:** Wall shear stress, pc pipes, coal particle size, air flow rate.

## 1. Introduction

Major percentage of electrical energy is produced through combustion of coal in many thermal power plants. Tangentially fired coal fired boilers are the mostly used type of boiler in the power generation [1]. The coal combustion process in thermal power plant consists of phenomena such as turbulence, heat transfer by convection and radiation, and chemical reactions. Now we need to see how a typical coal fired power plant operates. First the coal from the stock yard is sent to mill to pulverize into powder. The pulverized coal is carried into boiler through the pulverized coal pipe by the primary air and a blower is used to blow the heated air. The combustion takes place and a fireball forms due to the tangential firing of coal and fuel oil at four different corners. The economizer is the part in which the feed water is reheated by waste heat released from the exhaust gases exiting the boiler. This is a waste heat recovery to increase efficiency. The fireball of burning coal in the boiler will heat up the surrounding water walls that flows up the tubes.

The water flowing in the tubes absorbs heat released by heat flux and radiation from the fireball to the tubes. Partially, the water in the tubes are converted into steam. Then the mixture water and the steam, which is still not fully heated for turbine conditions in the tubes are transferred to the steam drum

at top of the furnace. In the boiler drum, separation occurs as the warm feed water flows to the steam drum, whereas the liquid water flows in the down comers on the outer part of the boiler and then to the bottom of the boiler. The steam from the steam drum is transferred to the primary super heater in which the steam temperature is raised to extremely high temperatures and then transferred to the secondary superheaters. At the final superheaters, the hot flue gases flow (product of combustion) on the outer surface of the tubes which causes the steam to be heated to its desired temperature and pressure before it exit from the boiler heading towards turbine. The high pressure and temperature steam contains high amount of enthalpy in which it is converted to mechanical energy by rotating the turbine around 3000rpm. This rotational energy is converted to electrical energy in the generator. The steam from the high pressure turbine will be sent back to reheated region of the furnace to be reheated. This reheated steam will be delivered to intermediate turbine. The main steam that exits the high pressure turbine is reheated and known as reheated steam. The combustion energy from the coal will be transferred as heat energy to the water in the boiler. There will be condensation of steam due to transfer of enthalpy from steam to mechanical energy of rotating turbine, the steam experiences drop in temperature. The condensed steam from the low pressure turbine will be converted to liquid water. This liquid water undergoes the same cycle just like feed water heater at the economizer for the next cycle of steam heating. In order to increase the waste heat recovery, which in turn increase the overall efficiency of the boiler, there are high pressure and low pressure heaters are attached to reclaim heat energy and increase thermal efficiency of the plant. A typical power plant consist of several major parts. One of them is a mill in which the coal is grind into smaller particles and injected into boiler through airflow. In this study there are seven mill included to study effect of coal flow and air flow rate on the flow of each pipe. Each mill has four pipes entering the boiler at four different corners. This is important to enable the tangential firing that creates the fireball. The coal need to be grinded into smaller particles so that the surface area of the coal particles increase and there are more chances of complete combustion. Incomplete combustion can actually cause emissions like NOx and Sox [2, 3, 11] that is harmful the environment. Coal that is grind into powder form is actually easy to be carried by higher flow rate of air into the boiler. Once the coal is injected, it travels along with air along pulverized coal pipes into boiler. The surface area and of the all the pipes differ from each other due to the arrangement of the mill. Once entered the boiler the coal is burn to produce heat energy that heat up the water entering, and converting them into high pressure and temperature steam that rotates the turbine to produce the electrical energy. A typical power plant is divided into many systems namely air system, coal system and ash system. Ash is formed when coal is burned. The ash that is produced is divided into two types, fly ash and bottom ash. Fly ash is trapped in either flue gas desulphurization unit or at times the electrostatic precipitator. The flue gas is the combustion gas that is excreted out through a chimney. Bottom ash is trapped at the bottom of boiler. The correct amount of air is essential as it can cause incomplete combustion. The air system has primary air and secondary air. A research was done to accumulate the available information that is related to the current study. The finding focuses on effect of coal particle size on boiler performance, analysis of wall shear stress and flow inside pipes, thermal analysis of utility boiler and combustion pollution control of utility boiler. An investigation about online monitoring of coal particle size and flow distribution was done in coal-fired power plants. According to finding the fineness of the coal particles and the uniform distribution of diameter of the coal flow sent to the burners are important parameters to attain an effective and also a combustion in coalfield power plants. The authors of published paper studied the effect of a varying centrifugal classifier speed on coal flow distribution. Their finding concludes that the coal flow distribution towards the boiler was significantly improved when the particle size was the smallest. They also managed to find that the maximum deviation from the average flow rate was reduced from 14% at 73 rpm to 9% at 99 rpm [4].

A fundamental study the transport of floating particles was done. It as was about investigation on the transport of fluids composed of water and polypropylene particles. The results are displayed in relation to flow patterns; and the experimental results suggest that the size of the particles has a very small impact on the transport efficiency [5]. Besides, the flow rate and the volumetric concentration have strong and significant impact on transport efficiency, because of their large contribution to the

flow pattern. The best operating conditions are close to the limit deposition velocity, when the fully suspended pattern is reached. The solids with high velocity are then well transported with no waste of energy. The optimum concentrations, for a wide range of high efficiency are around 20–25 %vol. The effects of the particle size on combustion characteristics of pulverized coals under $O_2/N_2$ and $O_2/CO_2$ atmospheres were studied and compared. The findings summarize four results. Firstly, effect of the particle size on the combustion of pulverized coal is greater than the effect of O2/N2 atmosphere. The effect of the particle size on combustion characteristic differs significantly betweenO2/N2 and O2/CO2 at the low O2 concentration. The changes of combustion characteristic fluctuate with the O2 concentration during O2/CO2 atmosphere. The O2 diffusion rate is the main reason of combustion in the O2/N2 condition, while the product release rate has a significant influence on combustion in the O2/CO2 atmosphere. The fluctuation of combustion characteristic is related to the rate of reaction. A particle which is big in size have lower rate of reaction due to the fact that the exposed surface area is small [6]. Analysis of wall shear stress around a competitive swimmer using 3D Navier–Stokes equations in CFD was done by C.V Popa and H Zaidi [7]. The authors of the paper studied the wall shear stress around a competitive swimmer during underwater glide phases occurring at the beginning and at every turn. The effect of different types of head position studied against wall shear stress. The head positions are namely lifted up, aligned and lowered. Additionally the static pressure distributions is analyzed. The velocity of swimmer are fixed at three different rates which are 1.4, 2.2 and 3.1 m/s. The authors also studied the effect of head configuration on wall shear stress under constant velocity. An important assumption in this study is the flow around the swimmer is turbulent. Their findings show that the wall shear stress increases with the velocity of the swimmer. A study on Computational fluid dynamics (CFD) analysis of single- phase and two phase flow was done. This study was performed in a 90 degree horizontal to vertical elbow with 12.7 mm inside diameter. In order to investigate the effects of different phases, three different combinations consisting of varying velocity of air and water is incorporated. Pressure and velocity profiles at six locations displayed a hike in pressure at the elbow geometry with decreasing pressure as fluid leaves from the elbow. Similar pattern of pressure drop observed for both single-phase and multiphase flows. Comparison of CFD results with available empirical models showed acceptable range of deviation. When the velocity increases the pressure drop increases. This conclusion was made and was applicable for single phase and multiphase [8]. Next X Yan, made a study on Modeling of the Flow within Scaffolds in Perfusion Bioreactors. Although the experimental study over a bioreactor is very complicated and almost impossible, the usage of cfd software enabled him to study the wall shear stress on perfusion bioreactors against different flow rates of fluid. The finding of this study will allow for better control strategies in scaffold fabrication and cell culturing experiments. His finding concludes that the effect of flow rate is significant on wall shear stress on the bioreactor. Flow rate is a controllable parameter in the cell culture process. The higher he flow rate the higher the wall shear stress on bioreactor. The flow rate and walls hear shows a linear relationship. The results also proves that the shear stress value is also affected significantly by the value of the strand diameter and horizontal span [9]. One of the most important elements in electricity generation is the balanced flow of coal and air. This balance need to be achieved at four corners of firing so that a fireball can be created. If the coal and air flow is not in the proper balance, we may face fouls like non uniform combustion in the furnace which is undesired. The coal and air balancing in a power plant is done using CFD. Devices like orifice are used to balance the coal air flow because not all the pipes are same in size and symmetrical. Therefore it is important to place orifice at right point. There was an estimation the pressure drop coefficients with both clean air and coal/air flows in order to select the appropriate size of the orifices. The results implies that the pressure drop is heavily dependent on the piping system geometry [10].

## 2. Methodology
There were two different configurations namely configuration 1 and configuration 2. Configuration 1 involves the study of wall shear stress against coal particle size under constant air flow rate. The second configuration involves the study of wall shear stress against air flow rate under constant particle size.

The current study regarding wall shear stress requires full knowledge on how these pc pipes are arranged. As mentioned above, there are seven mill with each mill contains four pipes heading to boiler at four different corners. This is important to enable tangential firing. All four pipes are not identical, as they have different length and area. There are total of 28 pipes available, but not all pipes are studied. For simplicity only pipes of mill 1, mill 2 and mill 7 is studied. The reason for the choice is that mill 1 and mill 2 are at opposite ends and mill 7 is in the middle. So choosing these three mills is appropriate because an overall conclusion can be made regarding all mill and pc pipes. A few figures describing the pipes and the arrangements of pipes are shown below.
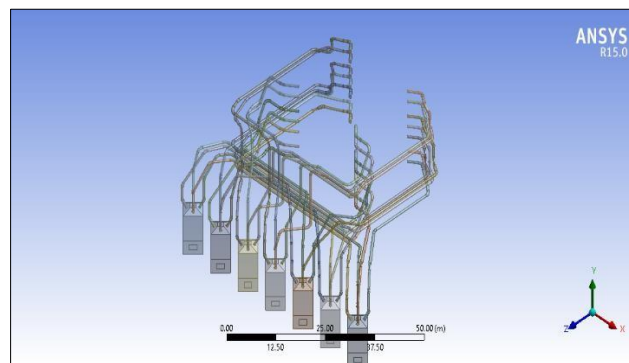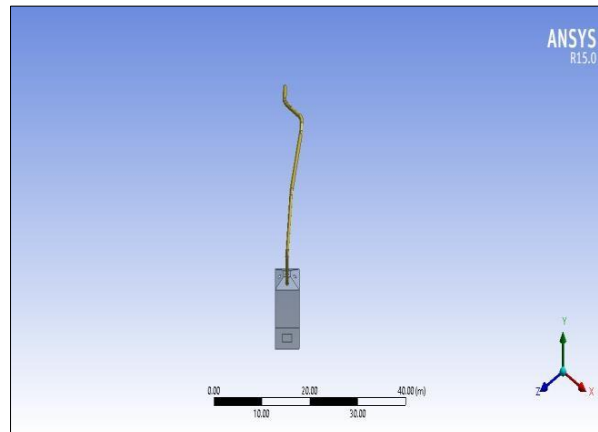


**Figure 1.** Arrangement of pc pipes leading to boiler

As we compare, the first pipe from mill 1 as shown in figure 3 and the first pipe from mill 2 shown in figure 4 is not same and completely different in geometry and arrangement. Same applies to all other pc pipes. Every pc pipes have different dimensions from each other.
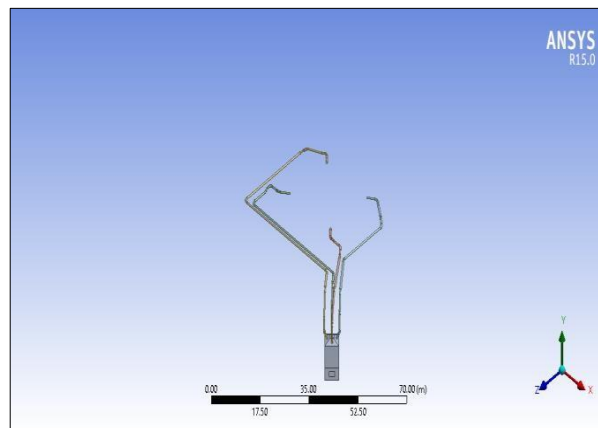


**Figure 2.** Mill 1 with all four pipes

**Figure 3.** Mill 1 with pipe 1 only
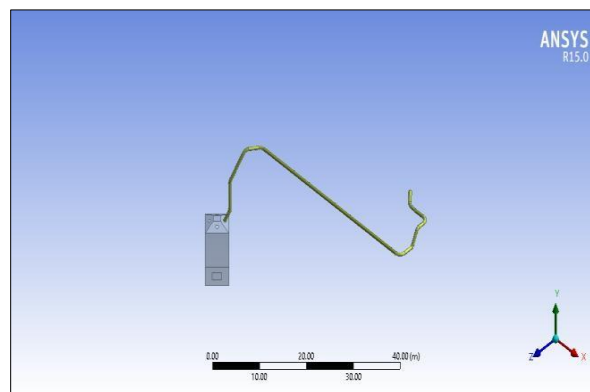


**Figure 4.** Mill 2 with pipe 1 only

There are total of 12 pipes studies (4 for each mill and 3 mills studies), but only few figures are shown here to illustrate the arrangement and construction of pc pipes of a utility boiler.

After the walls were defined individually, the mesh was imported to Ansys fluent software. The mesh independent study was done to select appropriate mesh configurations against result accuracy. To enable the simulation to be faster, the mills were studied one by one. For instance, in order to study the wall shear stress in mill1 which is named as mill10, the other mills were removed from the file. This will enable the simulation to be faster. Although other mills are removed, it does not affect the accuracy of the results because by default setting, the mills operate independent of other mills. As mentioned earlier there were two configurations were carried out. Both configuration was run in Ansys fluent.
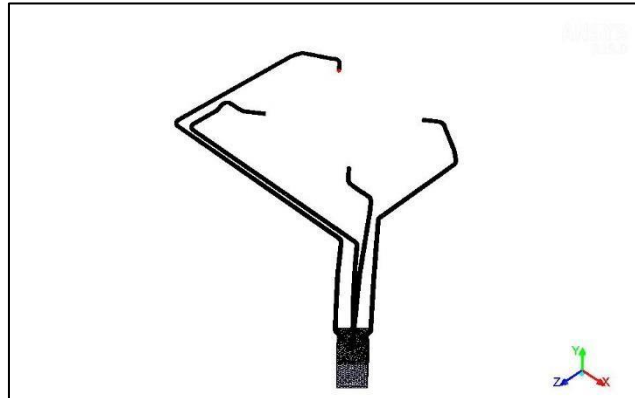
**Figure 5.** A screenshot of fluent showing mill1 before simulation and all other mills have been removed for faster simulation

*2.1 Running configuration 1: Constant air flow rate with varying coal particle size*
To achieve the objective which is to find out the relationship between coal particle size and the corresponding wall shear stress, the range of particle size to be examined are from 70 microns to 500 microns. This is the typical range of coal particle size globally. Under injections the coal flow rate is set to 12 kg/s and the coal particle size is set 70 microns. The air flow rate is set at 64 kg/s. The simulation of configuration 1 only involves changing coal particles size. Others parameters are kept constant. A turbulence model of K-Epsilon was used. The wall of pc pipes are set to be stationary wall and the material is aluminum. The coal that is injected is known as coal-mv in fluent software. The velocity of coal entering the mill is set to be 50m/s. Coal is release from surface of coal flow inlet. The outlet of the mill is pressure outlet. After the simulation is complete within acceptable range of error, the CAS file is saved with dat file. Under result report, the surface integral option is selected and the wall shear stress of the pc pipes is computed as area weighted average. The wall shear stress is computed in Pascal (Pa). Then the entire procedure is repeated with 100microns, 300 microns and 500 microns. A graph of wall shear stress against coal particles size is plotted and the trend is observed.

*2.2 Running configuration 2: Constant particle size with varying air flow rate*
Second configuration is done at coal flow rate of 12kg/s and coal particle size of 70micron. The airflow rate is varied from 64kg/s, 74kg/s, 84kg/s, and 94kg/s. Other parameter and setting were same as configuration 1. For this configuration only mill 1 and mill 2 is studied. Throughout the simulation the coal flow rate is set to 12 kg/s. The reason behind this is that increasing coal flow rate will cause more NOx and SOx emissions. Furthermore increasing coal flow rate increase overall coal consumption. Coal is a non renewable energy, so the usage should be limited. The wall shear stress is computed using the same procedure as configuration 1.

Once both configuration are done, graphs of wall shear stress against coal particle size is plot for configuration 1 for all three mills. Then the graphs of wall shear stress against air flow rate is plotted. Trends of both graphs are analysed.

**3. Results and discussion**
For configuration 1, the air flow rate is fixed at 64kg/s and coal is injected at various size ranging from 70 microns to 500 microns. The graph below show the coal particle size and the corresponding wall shear stress that is computed as area weighted average.
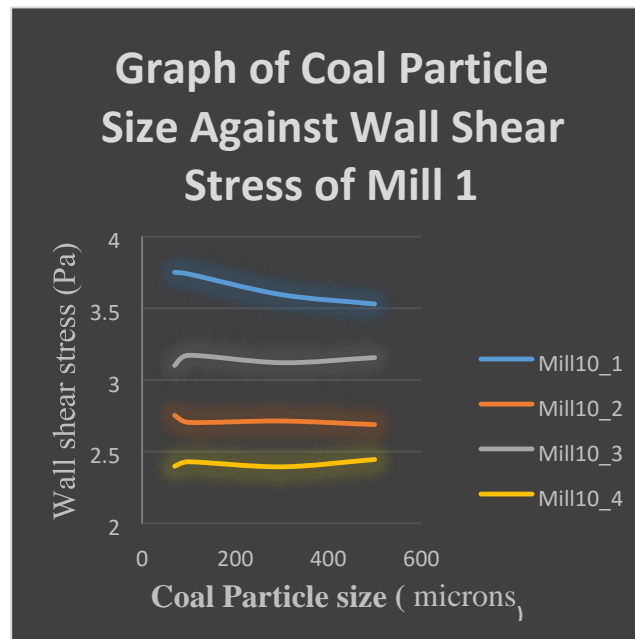
**Figure 6.** The graph of wall shear stress against coal particle size for mill 1

Based on the graph, the wall shear stress value for all of the four pipes of mill 1 does not show a significant change and almost constant throughout the flow. There is a slight drop can be observed for Mill10_1 which is the pipe 1 of mill 1, in which the wall shear stress reduces as the coal particle size increases. Since the coal are driven by the air flow, the velocity of coal is dependent on air flow rate. For the same amount of force, the smaller object with smaller mass tend to move faster than a bigger object with bigger mass. Same happens within pc pipes with coal particles. Higher the velocity higher the wall shear stress [7,9]. The force here is the air flow. Since air flow is fixed at 64kg/s, smaller particles of coal moves faster with higher velocity compared bigger particles. This is the reason why small coal particles at 70 microns have higher wall shear stress than other particle size like 300 microns and 500microns in mill10_1. For other pipes, for instance mill10_2, the trend line is almost constant. Nevertheless, for mil10_2, the highest wall shear stress is at 70 microns at a value of 2.75 Pascal. Mill10_2 shows same characteristics as mill10_1 for 70 microns. As the coal particle size increase in mill10_2 the wall shear stress is almost uniform. There is no significant change that was seen in the graph. It is not valid to compare mill10_1 with mill10_2 because both are different in geometry. Since the wall shear stress is computed as area weighted average, the area of the pipes play an important role in the average value of wall shear stress. As summarized in table each pipes have different area. From the table it is shown that mill10_4 has the highest surface area compared to all three pc pipes. Thus the wall shear stress in mill10_4 is the lowest in the graph 1. The bigger the area the smaller the wall shear stress. The trend line of mill10_3 also similar to mill10_2, in which highest wall shear stress is observed at small range of particles ranging from 70 to 100 microns. Furthermore the number of bends in the pipe is also an important factor in studying wall shear stress. The bend in a pipe with cause drop in velocity of particles flowing through. In comparison mill10_2 have more bends compared to mill10_1 with is almost a straight pipe. In short, the geometry of the pipe is important parameter in considering the wall shear stress [9].The contours of wall shear stress is also included to display the overall flow behavior.
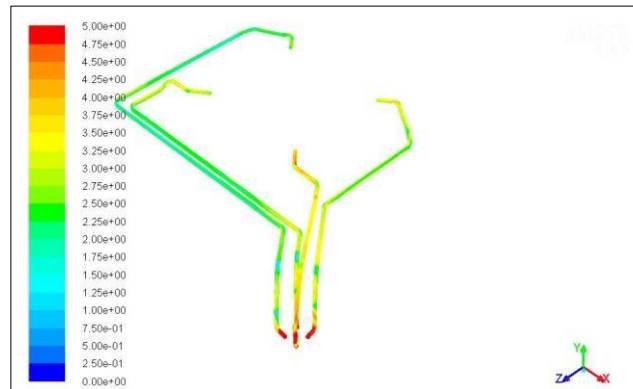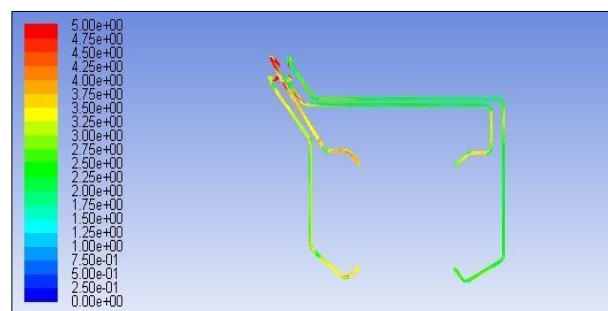
**Figure 7.** Contours of wall shear stress of mill10 at coal particle size of 70 microns

The figure above shows contour of wall shear stress of mill10 when particles of 70 microns are injected. The highest wall shear stress is observed at the inlet of the pipe. This is because the injected has the highest velocity at the beginning of the pipe and experience a loss in momentum as it travels along the pipe. The drop in velocity in not very significant, thus the wall shear stress also shows only slight decrement. As for mill10_1, the contours have many reddish and yellow region, indicating higher average wall shear stress as shown in graph. The mill10_1 is the shortest pipe, thus the loss of momentum or the drop in velocity is least significant. This is why an almost uniform wall shear stress can be observed. Next is mill10_2, more green contours is observed as compared to mill10_1, this is because the length of the pipe is longer than pc pipe mill10_1. Since it is longer, the drop in velocity is much more significant compared to mill10_1, thus a more greenish region observed. It can also be seen blue contours at the bends of all the pipes, especially mill10_2, mill10_3, and mill10_4. This is due to the fact that bend in pipes causes the drop in velocity of the fluid flowing inside. So lesser the velocity, the lesser the wall shear stress on that bend region. The screenshots of mill10 injected with 100microns, 300 microns, and 500 microns of coal particle size are shown in below.
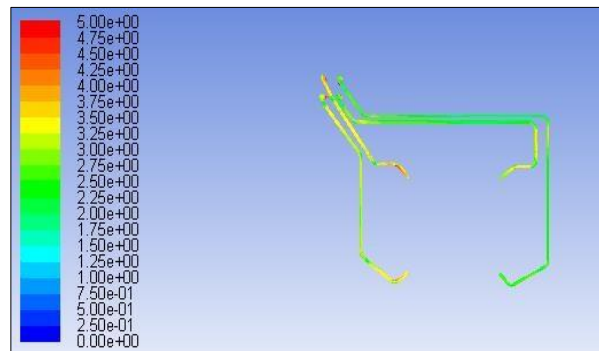


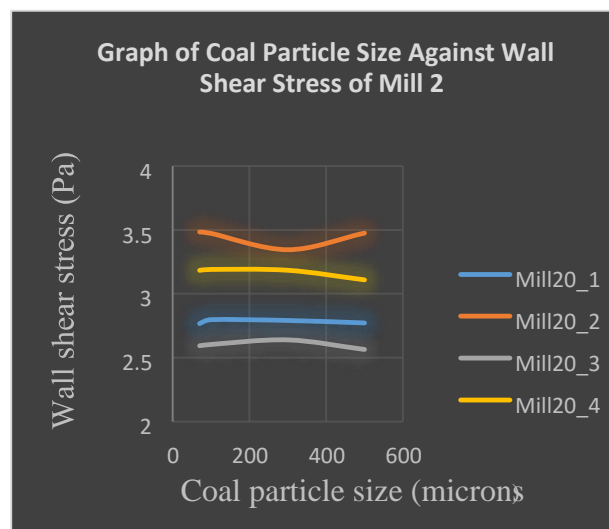**Figure 8.** Contours of wall shear stress of mill10 at coal particle size of 100microns



**Figure 9.** Contours of wall shear stress of mill1 at coal particle size of 300 microns

From the figure above, as the coal particle size is increased, it is observed that greener region is observed throughout pipe 2, 3 and 4, indicating lesser wall shear stress. There is also a slight drop of wall shear stress is pipe 1 which mill10_1 but not so significant. Similarly, the contours of wall shear stress of mill10 that is injected with bigger particle size of 300 microns shows less red regions compared smaller particles of 100 microns and 70 microns. Similar observations for coal particle size of 500 microns.



**Figure 10.** Contours of wall shear stress of mill 1 at coal particle size of 500 microns



**Figure 11.** The graph of wall shear stress against coal particle size for mill 2

Similar to mill 1, the wall shear stress of pc pipes of mill 2 did not display significant change and almost uniform. Only for mill20_2, there is a minimum wall shear stress observed at 300 microns and the wall shear stress increases beyond 300 microns of particle size. Although it increases, the percentage of increase is too small. The pipe that experience highest wall shear is mill20_2, in which it has the lowest area as shown in table 1.
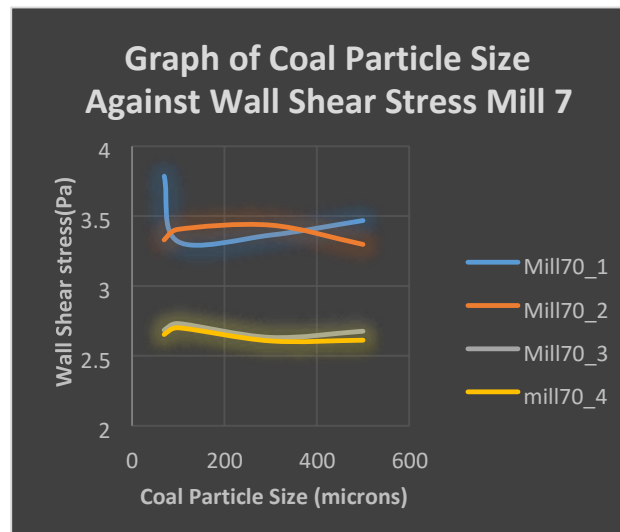
**Figure 12.** The graph of wall shear stress against coal particle size for mill 7

Unlike mill 1 and mill 2, the graph of mill 7 is little different as there is some intersection between the graphs. However, the pattern is almost linear for all four mills. The highest wall shear stress is observed at mill70_1 which has the smallest area. Mill70_1 and mill70_2 has almost same area, thus both of them have wall shear stress value close to each other. This is why we could see some intersection between the graphs. The graphs of mill70_3 and mill70_4 also very close to each other, thus their value of wall shear stress also very close to each other. From table 2, the area of mill70_3 and mill70_4 only differs a little. By observing figure 1, mill 7 is slightly special when compared to other mills because it is located in the center among all mills, and all four pipe coming out of the mill heading towards the boiler is almost symmetrical.  The contours of wall shear stress are shown below.



**Figure 13.** Contours of wall shear stress of mill 7 at coal particle size of 70 microns

Configuration 2 involves changing the air flow rate and computing the wall shear stress as area weighted average similar to configuration 1. The coal flow rate is fixed at 12kg/s and the coal particle size is fixed at 70 microns. The graph of air flow rate against wall shear stress is shown below. Only mill 1 and mill 2 is studied in this configuration.

The figure 14 shows the behavior of wall shear stress of the pc pipes of mill 1. Unlike the coal particle size, the air flow rate shows a significant increase in wall shear stress. The significant increases is observed in all four pipes.  However, the highest wall shear stress is for mill10_1, the shortest pipe with smallest area. For a constant particle, when the air flow rate increases, the velocity of particles in the pipe increases. The force that drives the coal particles is air flow. Higher the flow rate, higher velocity of particles, thus higher value of wall shear stress [9]. In this configuration the range of air flow is from 64kg/s to 94 kg/s only. For instance, with just air flow rate increase of 47 %, the wall shear

stress increases by 95 %. Thus, it can be concluded the effect of air flow rate is much more significant than effect coal particle size on wall shear stress.
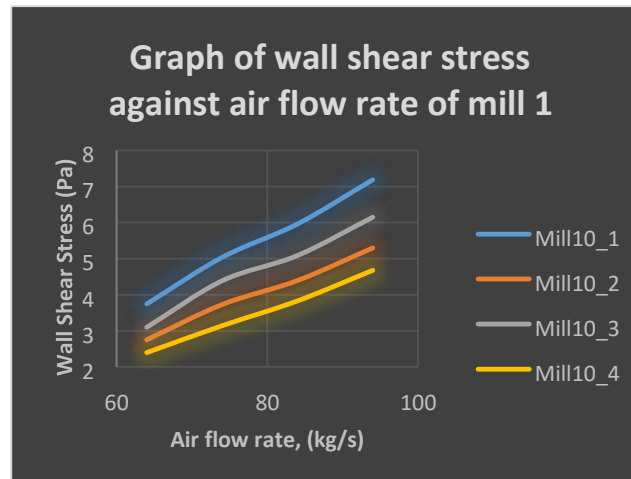


**Figure 14.** The graph of wall shear stress against air flow rate for mill 1
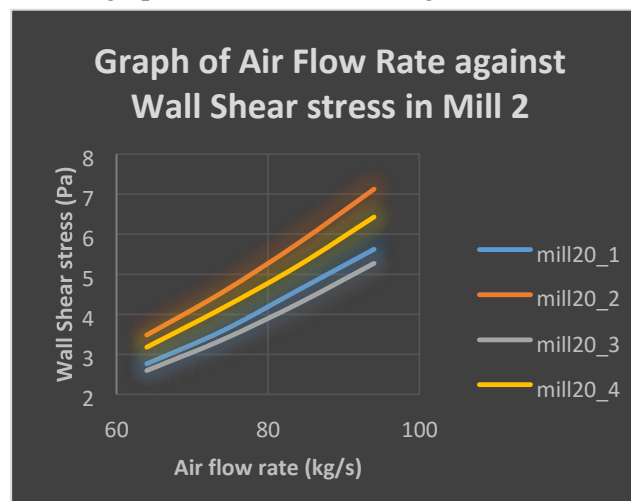


**Figure 15.** The graph of wall shear stress against air flow rate for mill 2

Similar to mill 1, mill 2 also exhibit same characteristics in which the wall shears stress increases with increasing air flow rate. An almost linear relationship can observed in both graphs. The highest wall shear stress is experienced by mill20_2, which has the smallest area based on table 3.1. Conversely the smallest wall shear stress is experienced in mill20_3 which has the biggest area among all the four pipes. In short, the air flow rate causes a very significant increase in wall shear stress compared to the coal particle size for both mill 1 and mill 2.

## 4. Conclusion
For configuration 1, the increase in coal particle size does not show significant increase in wall shear stress. However, most of the pipes that has been studied, the wall shear stress is reducing at higher coal particles size. Majority of the pipes displayed minimum value of wall shear stress in coal particle size ranging from 200-300 microns. In order reduce the failure rate of pc pipes due high wall shear stress, it is recommended to use particles of size ranging from 200-300 microns. However, although this range decreases the wall shear stress, on the other hand it can cause the increase of NOx and SOx emissions.

According to J Blondeau, the coal flow distribution towards the boiler was significantly improved when the particle size was the smallest [4]. Increasing coal particle size will cause significant increase in SOX emission [3,12-13]. Using higher particle size with smaller surface area exposed reaction, thus the chances of complete combustion reduces. This can adversely affect the thermal efficiency of the boiler. Furthermore, the grinder in the actual mill practically is not able to grind all coal particles to a single value of coal particle size like 70 microns. Usually the grinding process produces coal at no uniformly distributed particle size within a range. So as per my finding, although the smaller particles cause higher wall shear stress, it is still recommend to inject coal in the small particle range from 70- 100 microns because increase in coal particle size does not show significant drop in wall shear stress but cause significant increase in emissions [3,13]. The problem of uncontrolled emission is way too serious compared failure of pc pipes.

For configuration 2, the air flow rate showed significant increase in wall shear stress unlike coal particle size. So it is concluded that air flow rate ranging from 60-70 kg/ s will be best flow rate to be used in a utility of 700MW. Lower values of air flow rate produces lower wall shear stress. Moreover, higher flow rate will cause the air to fuel ratio of the combustion in the boiler to be affected. In order to balance the air- fuel ratio, more coal need to be injected. This will increase coal consumption. Improper air to fuel ratio increases the chances of incomplete combustion causes SOx and NOx emissions [13]. Contact of the nitrogen from the fuel with the oxygen within the combustion air is reduced there will be notable amount of decrease in the NOx formation.

**The objective of the study is achieved**. The effect of coal particle size on the wall shear stress is investigated and it is concluded that smaller particles will cause higher wall shear stress. Next objective which is the effect of air flow rate on the wall shear stress. The higher the air flow rate, the higher the wall shear stress. There is a linear relationship between air flow rate and wall shear stress. To enable most optimum operation of a utility boiler, it is best to use coal particle size of range 70-100 microns with causes least emissions and air flow rate of range 60-70 kg/s for an optimum combustion.

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