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Investigation of the Flow Inside Coal Pulveriser with Varying the Vane Angle

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ABSTRACT

Coal and natural gas are used to generate almost 93% of electricity in Peninsular Malaysia. While the use of coal in the energy industry increases, the impact of coal burning on the environment should be emphasized. Incomplete combustion in boilers frequently results in a substantial amount of unburned carbon in the ash and pollutant emissions. A key factor in resolving this issue is to improve classification quality by achieving a higher particle separation quality in which at least 70% of the coal particles leaving the classifier are smaller than 75µm. The effect of the flow inside the coal pulveriser with varying vane angles (45° and 60°) on classification in coal-fired power plants was investigated using three-dimensional (3-D) computational fluid dynamics modelling. The realisable k-ε turbulence model (RKE) with a detailed 3-D coal pulveriser geometry was used to solve the flow inside the coal mill, while the discrete phase model was used to solve the coal particle flow. The coal mill with a vane angle of 60° resulted in better escaped particles with 69.35% of the coal particles with 50-micron size escaped and 59.68% of coal particles with 75-micron size escaped from the outlet. The flow pattern inside the coal mill for the 60° vane angle model is also fine which is swirling from the bottom of the tank.

1. Introduction

The world's 7.9 billion population is currently growing at a rate of 81 million people per year. The demand for electricity has increased precisely to 66% from 2000 to 2021 due to population growth more than other industries [1]. Nevertheless, it found that close to a quarter population did not have appropriate access to electricity. Energy consumption increases in tandem with the increase in human population until the world's energy supply is no longer adequate to fulfil all the world's energy demands [2]. Besides, the world needs to expand the capacity of the power station and technologies to ensure the user can get benefits in terms of daily work and other activities. With the expansion of electric power stations, the world environment also needs to be taken care of to ensure it is free

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from any particles or gases that can cause pollution. In addition, when it comes to energy production and consumption, there has been a strong link established between them and negative environmental consequences to the point where the 1997 United Nations summit in Kyoto, Japan, had to include a resolution establishing the Kyoto Protocol, which limits carbon dioxide emissions into the atmosphere [3]. The power generation industry, particularly coal power plants is known to contribute a significant impact towards the environment. Proper technology is needed because the processes to generate electricity from coal produce carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NO_x) and other harmful gases.

The National Energy Policy established the Environmental Objective in 1979 to "minimize the negative environmental impacts on the energy supply chain, i.e., energy production, conservation, transportation, and utilization". Even though coal is known to pose significant challenges, such as greenhouse gas emissions and air pollution, it continues to play an important role in energy supply as gas prices rise. Peninsular Malaysia has a total installed capacity of 27,224.7 MW, with coal-fired power plants supplying approximately 15,850 MW [4]. Figure 1 depicts a visual that represents the coal power plants installed in Malaysia between 1990 and 2020.

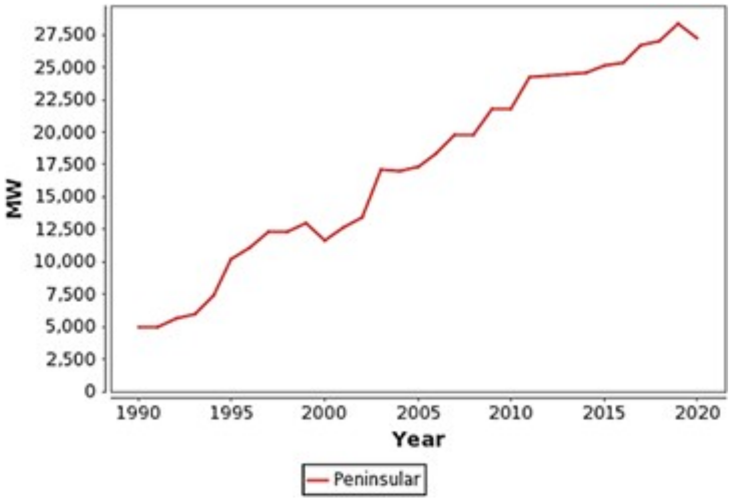

Fig. 1. Total installed energy capacity Peninsular Malaysia

Coal has been beneficial as a fossil fuel for a range of industrial and domestic applications for a long time. Many nations' economic success has been bolstered by the vast distribution and plentiful availability of coal resources, either directly via their own resources or indirectly through access to the global coal trade, which has aided their growth and allowed them to flourish. The public's opinion of coal has worsened even though its usage has increased because of environmental concerns and changes in the political climate in recent years[5]. With increasing concern about the role of coal in contributing to greenhouse gas emissions, notably CO_2, coal's position in the energy mix is being re-examined, and the search for other sources of energy is being re-launched. The coal industry will continue to be the world's second-largest energy source and a crucial feedstock for many industrial uses in the face of these problems in the next decades.

Energy consumption increases in tandem with the increase in human population until the world's energy supply is no longer adequate to fulfil all the world's energy demands. When it comes to energy production and consumption, there has been a strong link established between them and negative environmental consequences to the point where the 1997 United Nations summit in Kyoto, Japan, had to include a resolution establishing the Kyoto Protocol, which limits carbon dioxide emissions into the atmosphere [6].

To reduce the negative environmental impact that is caused by emissions from the incomplete burning of coal, some researchers suggest the use of carbon capture sequestration (CCS) to lower the emission discharge to the environment. Carbon capture technologies involve capturing the CO_2 at power stations, transporting it to storage locations (usually deep underground) and isolating it there. They use carbon capture and sequestration (CCS) as a viable mitigation strategy for reducing greenhouse gas (GHG) emissions in fossil-fuel power plants and discuss the impacts on the sustainability of freshwater resources [7]. Figure 2 shows the plant efficiency with emission intensity value when using carbon capture.

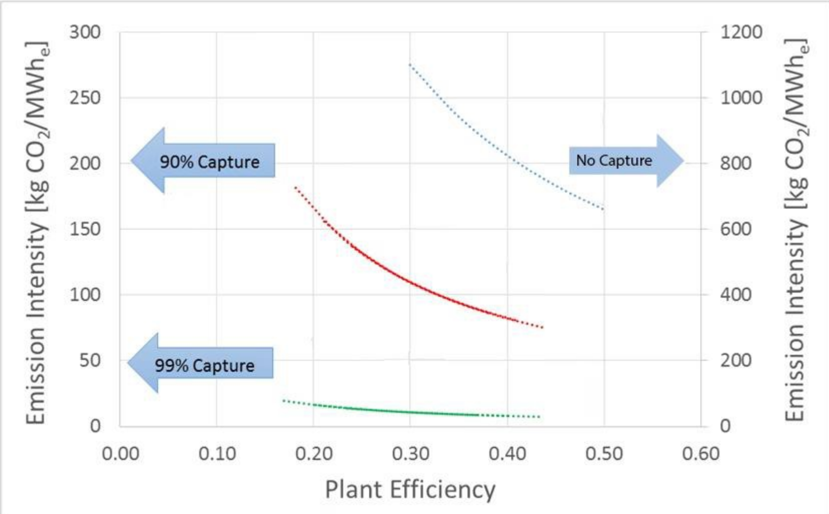

Fig. 2. Direct CO_2 emissions from coal-fired power stations with no capture, and at 90% and 99% capture rates

Furthermore, the Japanese government is promoting clean coal technology (CCT) research and development to increase energy efficiency and carbon capture capability while lowering pollutant emissions [8]. Various high-efficiency combustion techniques with low pollutant emissions have been developed and applied in the country as the established and highly reliable coal utilisation method [9]. The flue gas and ash treatments at the downstream side of the boiler, as well as the advancement of SO_2 removal and low NO_x combustion technology, have resulted in Japan having the lowest levels of NO_x emission and dust generation during coal combustion in the whole globe. Japanese manufacturers have created unique low NO_x-emission pulverised coal burners with enhanced ignitability and intra-flame denigration capability by using the separation of dense and lean pulverised coal streams and a multilayer charge of combustion air [10]. Additionally, in the main burner zone of the boiler, intra-furnace denigration is accomplished by using the residual hydrocarbons or the hydrocarbon created from a tiny amount of fuel oil delivered from the top of the burner [11]. On the other side, improving the thermal efficiency of power plants is crucial for lowering costs while simultaneously reducing CO_2 and other pollutant emissions.

The method of controlling the coal size in a coal pulveriser has been used for a long time ago. Pulveriser was invented in 1890 by John P. Parker a black businessman [12]. A pulveriser, also known as a mill, is a mechanical device used to grind a wide range of materials. It is one of the most important power plant components because it is responsible for converting the energy stored in coal into electricity. To ensure efficient combustion, coal is ground into fine particles (100 µm) using pulverisers before being put into a boiler. To meet the requirements of a pulverised coal (PC) boiler, the coal must be reduced in size using a coal pulveriser. Coal is ground into a fine powder and distributed to the burners for ignition after being mixed with air. Plant performance can be dramatically improved by controlling the fineness and the air mixture [13]. In coal-fired power plants, the coal pulveriser is located downstream and distributes the pulverised fuel to the furnace burners [14]. A vital part of the plant is the classifier, which is situated above the pulveriser. It is intended to return larger coal particles to the mill for additional grinding while discharging fine particles under a predefined particle size threshold. Large particle rejection is essential to clean technology since it enhances overall combustion and lower emissions.

Coal particulate size requirements vary depending on the coal properties and power plant requirements [15]. The impacts of major classifier parameters on particle centrifugal and gravitational forces within the classifier are of special interest. With a fine understanding, it will help to select the appropriate classifier parameters to be taken so that the correct particulate can be liberated finely [16]. This will facilitate the improvement in the total efficiency of coal power plants and minimise the formation of harmful gases during fuel combustion, NO_x. This research will take advantage of contemporary Computational Fluid Dynamics (CFD) simulation software.

2. Methodology

2.1 The Geometry of Coal Pulveriser

The coal pulveriser was designed and modelled based on the high-speed mill. Basically, this model has six main parts such as coal inlet, pulverised coal outlet, primary air inlet, rotating bowl, classifier vane and grinding roller but has been simplified because it is suggested to neglect the unnecessary part for flow simulation [17]. Figure 3 shows the main part of the coal pulveriser in this flow simulation. It also represents the boundary condition for the project. For example, the body and vane represent the wall for boundary conditions. The geometry model was designed by using SolidWorks and imported into Ansys Workbench 2021 R1 [18].

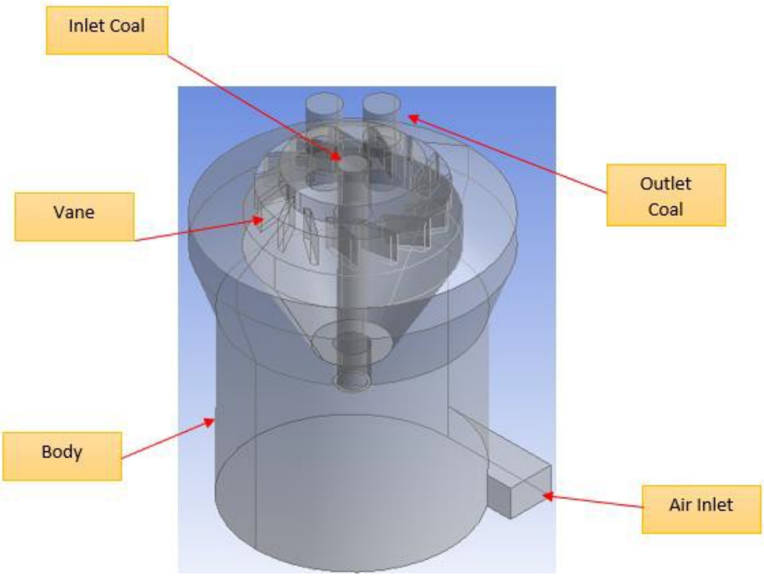

Fig. 3. Model of coal pulveriser using SolidWorks software

Fluent was utilised for simulations and post-simulation data interpretations. To get the desired simulation result, the mesh was adjusted until the skewness was below 0.85. In this simulation, the size of the element was set to 0.039 m. The relevance centre in the sizing tab was set to fine and in the quality tab, the skewness was reduced to 0.85 and the smoothing was high. For the assembly meshing method, the tetrahedron meshing method is used to generate the mesh model [19]. The total nodes and elements of this mesh model are 219,607 and 1,110,327, respectively. Figure 4 shows the model after meshing was applied.

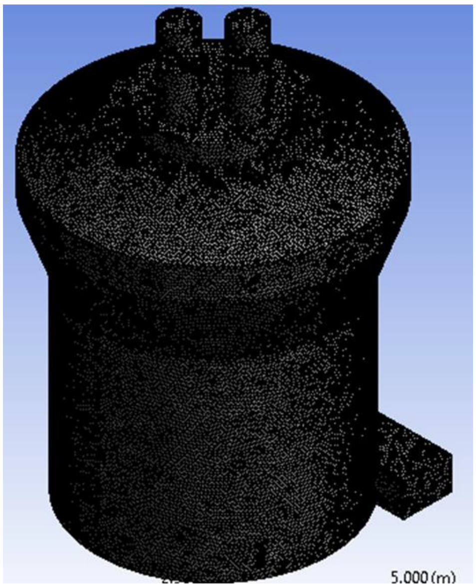

Fig. 4. Mesh model for coal pulveriser

Due to the classifier's design and operation, the flow of the air-coal mixture is typically turbulent inside the coal classifier [20]. To replicate the flow inside the coal pulveriser, a precise turbulence model should be used. Therefore, in the numerical simulation of this work and related investigations, the Reynolds Averaged Navier-Stokes (RANS) equations were used. The realizable k-epsilon (RKE) turbulence model was used to simulate the flow inside the coal pulveriser. It was developed based on the standard k-ε model. Table 1 shows more details about the setup of this project.

For boundary conditions, the air inlet was defined as inlet air with a velocity of 15 m/s, 17 m/s, and 20 m/s while the discrete phase boundary conditions type was set as reflect. For the coal inlet, it was defined as inlet coal with a value of 15 kg/s and the direction specification method was normal to the boundary. The particle size of coal injection is 50 µm, 75 µm and 100 µm. Hence, the particle flow was solved using the discrete phase model (DPM).

Table 1
Solver setup with description

Solver setup	Description
Fluent Launcher	Double Precision
Solve Type	Pressure-Based
Velocity Formulation	Absolute
Time	Steady
Gravity	Y = - 9.81 m/s^2
Viscous Model	RKE (Realizable k- epsilon)
Discrete Phase Model	Injection (Anthracite) = On

3. Results
3.1 Velocity Analysis

The section starts by looking at the effect of the inlet velocities and vane angles on the velocity profile inside the coal pulveriser. To help understand the analysis better, the illustration of the coal pulveriser and four areas were analysed and have been named level A through level D. Figure 5 shows more detail for each level.

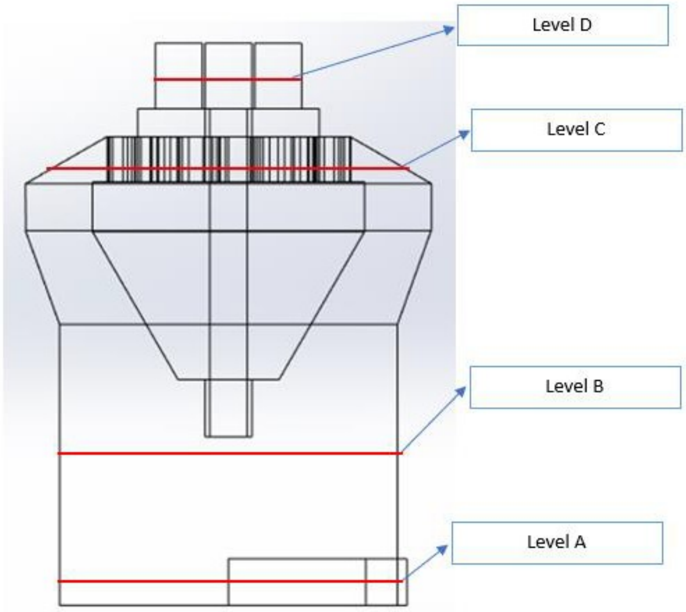

Fig. 5. The classifier and four level velocity analysis

Figure 6 and Figure 7 show the velocity profile on the coal pulveriser's isometric view. According to the figure, the velocity magnitude ranged from a maximum velocity of 17.56 m/s to zero velocity for a 45° vane angle while for a 60° vane angle, the range is between 19.52 m/s to zero velocity. The velocities at the air inlet, coal inlet and outlet were greater than the velocities inside the pulveriser. The velocity decreases away from the inlet and then increases toward the outlet. Figure 6 shows the flow of velocity inside the tank is unsteady while Figure 7 clearly shows that the air flow is swirling due to reflection when it hits the pulveriser wall.

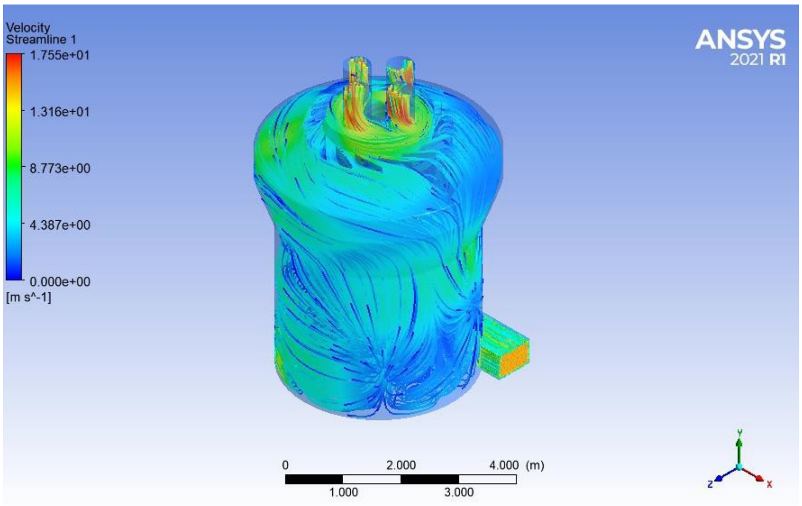

Fig. 6. Velocity streamline of 45° vane angle

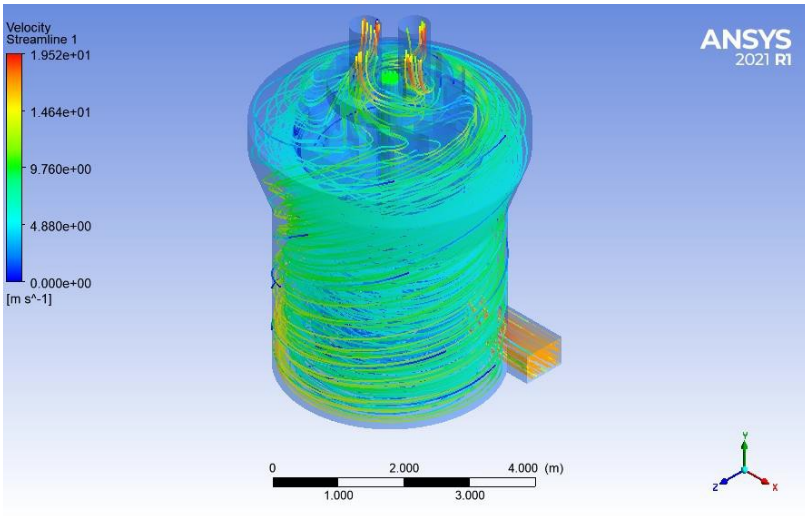

Fig. 7. Velocity streamline of 60° vane angle

Figures 8 and 9 show the velocity vector for the 45° vane angle and 60° vane angle. Although the 45° vane angle motion is unsteady flow, it transforms into swirling motion when it enters the vane region while the 60° vane angle shows consistent swirling motion from the initial process.

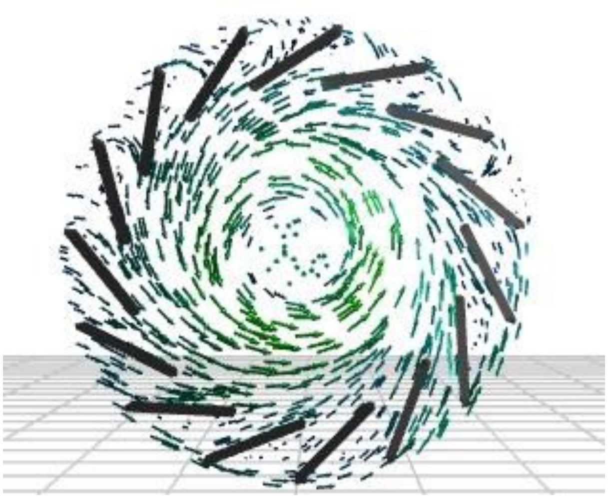

Fig. 8. Velocity vector of coal pulveriser 45° vane

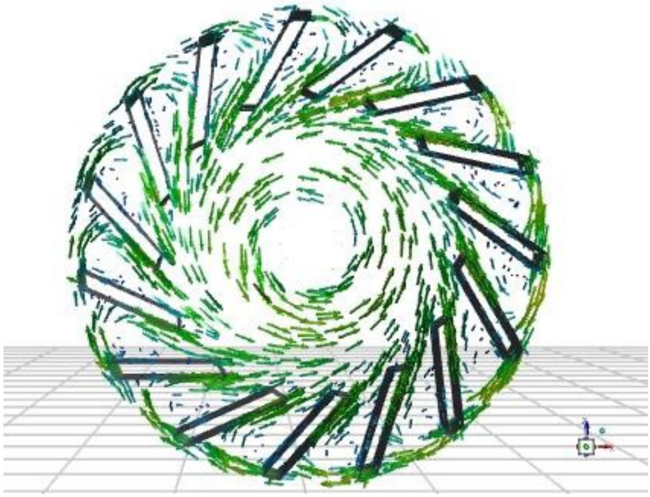

Fig. 9. Velocity vector of coal pulveriser 60° vane

3.2 Air Flow Analysis

The coal particles are carried by air flow into the area outside the cone classifier by the air inlet near the bottom of the bowl mill. The air then rises in a swirling motion and enters the vane area. The velocity profiles must be evaluated because the flow structure determines the particles by moving the particles upwards [21].

Two types of coal pulverisers were assigned with two different angles. Besides, each pulveriser model was run with three velocities and three particle sizes. To help understand the analysis better, Table 2 was created to make it more arranged. All the measurements were done from each level from level A to level D.

Table 2
The flow analysis of models 45° and 60°

Vane Angle (°)	Velocity (m/s)	Particle size (μm)
45	15	50
		75
		100
	17	50
		75
		100
	20	50
		75
		100
60	15	50
		75
		100
	17	50
		75
		100
	20	50
		75
		100

3.3 Effect Velocity with Varying the Vane Angle

Figures 10 to 13 show the velocity profile resulting from varying the vane angles for injection of velocities 15 m/s from Level A to Level D. The velocity magnitudes show differences at the inlet air region (Level A). The velocity decreases at the middle tank (Level B) for a certain time and rises again at Level C and Level D. This happens due to the flow of particles from huge space (low pressure and low velocity) entering small space (high pressure and high velocity) until discharge to outlet PC (Pulverized Coal) which is small diameter size. For velocities of 17m/s and 20 m/s, the flows show an almost similar pattern.

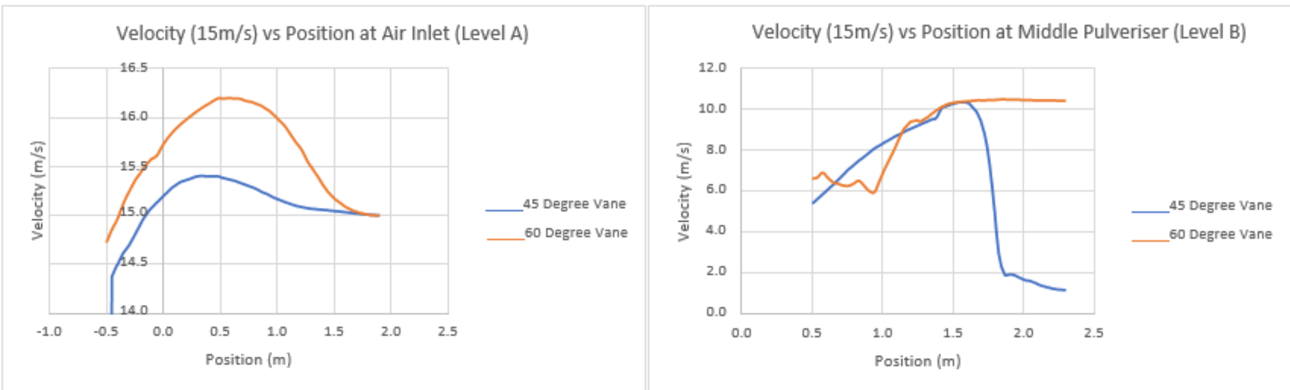

Fig. 10. Velocity profile (15 m/s) at inlet (level A) and velocity profile (15 m/s) at middle pulveriser (level B)

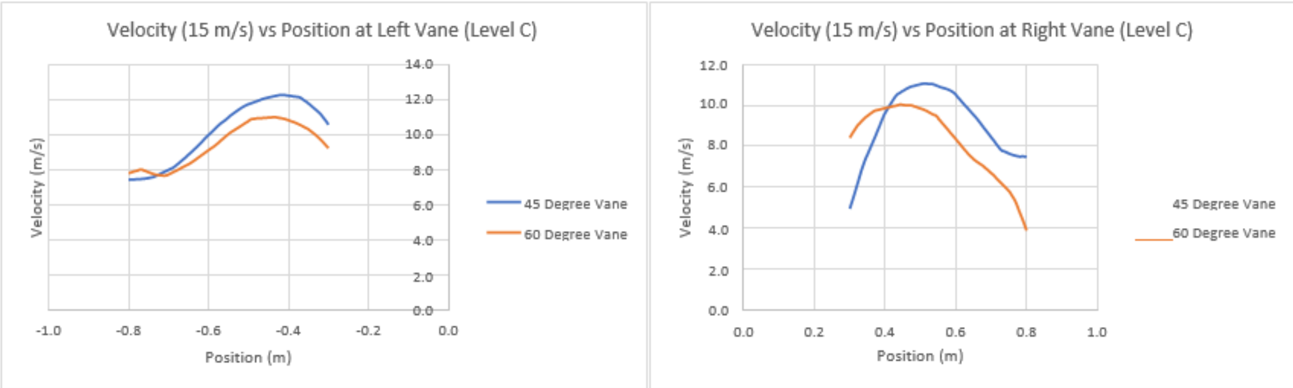

Fig. 11. velocity profile (15 m/s) at left vane (a) and velocity profile (15 m/s) at right vane (b) at level C

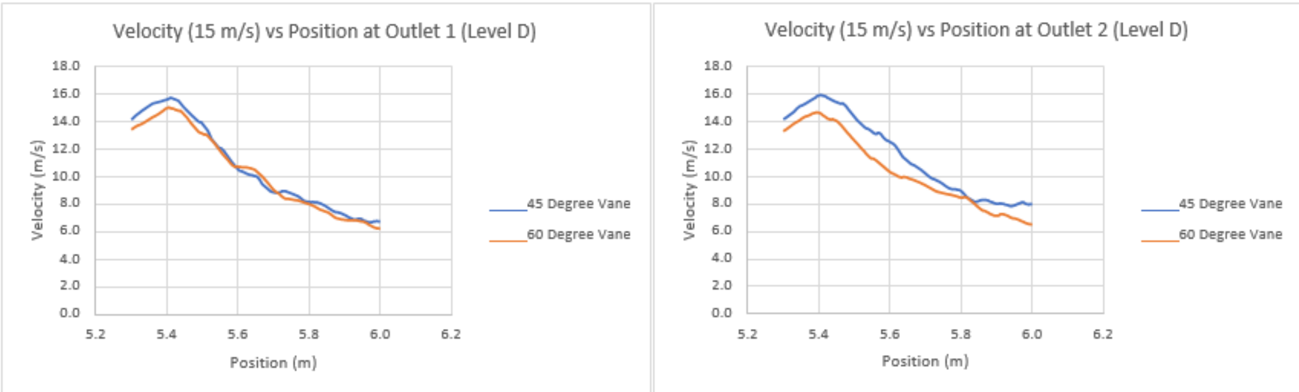

Fig. 12. Velocity profile (15 m/s) at outlet 1 (level D) and velocity profile (15 m/s) at outlet 2 (level D)

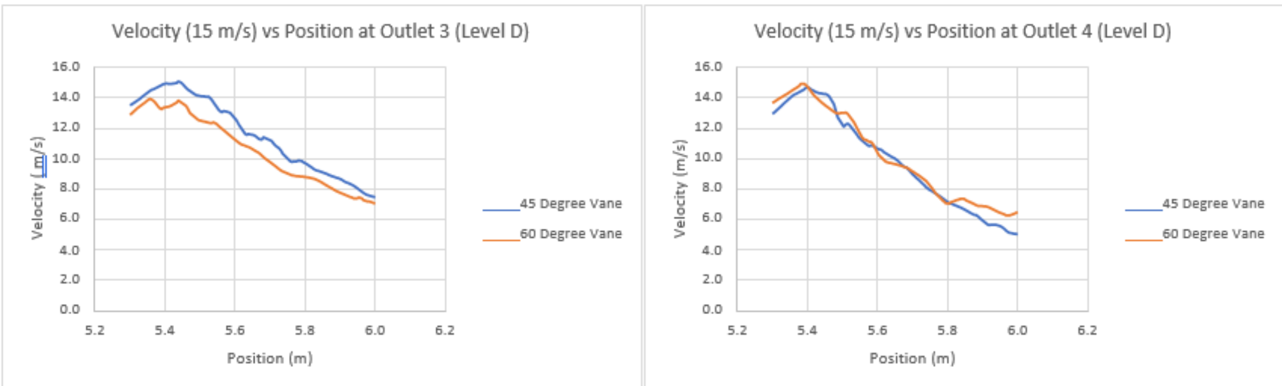

Fig. 13. Velocity profile (15 m/s) at outlet 3 (Level D) and velocity profile (15 m/s) at outlet 4

3.4 Effect of Vane Angle with Different Velocity

This section will discuss the effect of vane angle with different air inlet velocities in both pulveriser models.

3.4.1 The velocity profile in coal pulveriser

Figures 14 to 19 show the velocity profiles of the whole area in the coal pulveriser for inlet velocities 15 m/s, 17 m/s and 20 m/s at Level A through Level D. The vane angle is 45°.

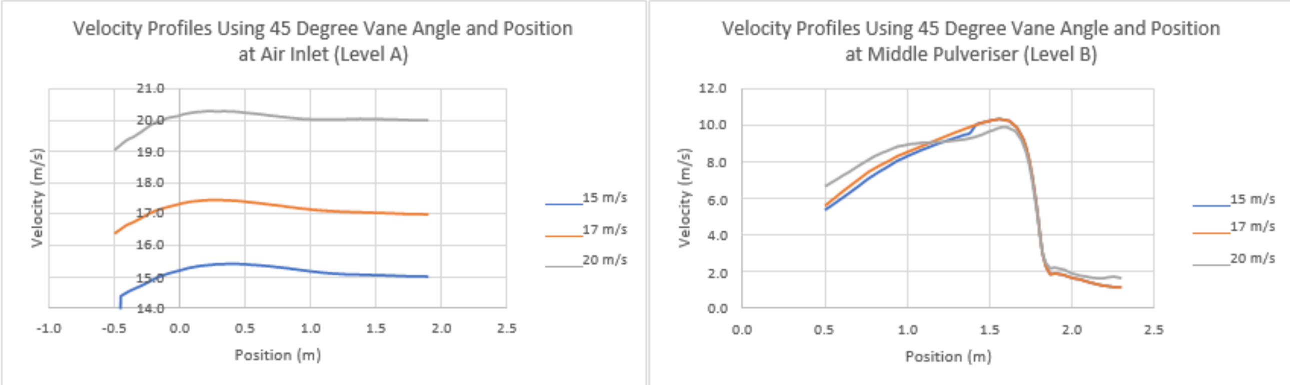

Fig. 14. Velocity profiles coal pulveriser at air inlet (level A) and middle pulveriser (level B) for various inlet velocities (45° vane angle)

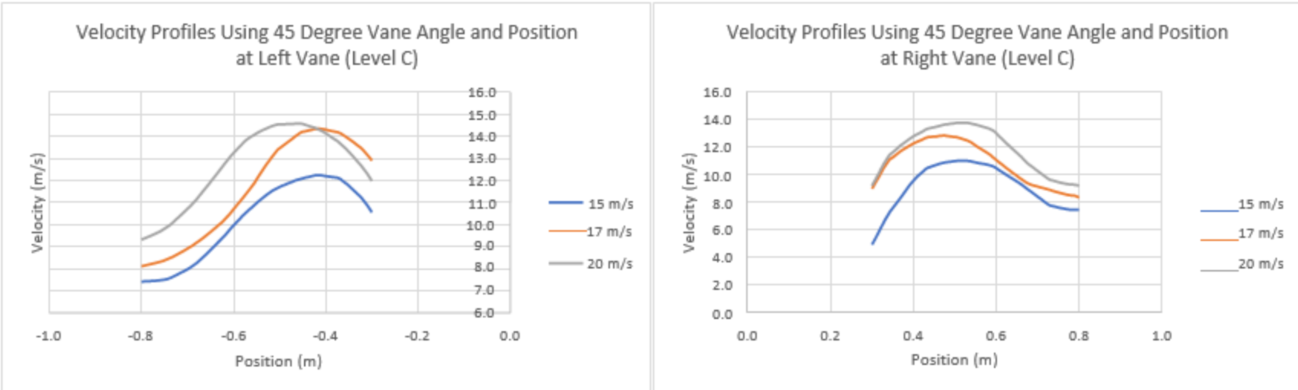

Fig. 15. Velocity profiles in coal pulveriser at left vane (level C) and right vane (level C) for various inlet velocities (45° vane angle)

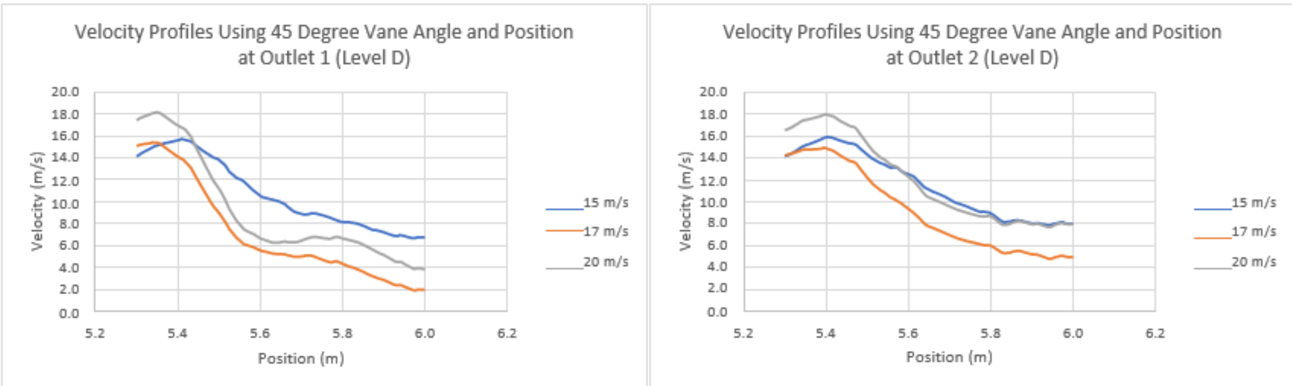

Fig. 16. Velocity profiles in coal pulveriser at outlet 1 and outlet 2 (Level D) for various inlet velocities (45° vane angle)

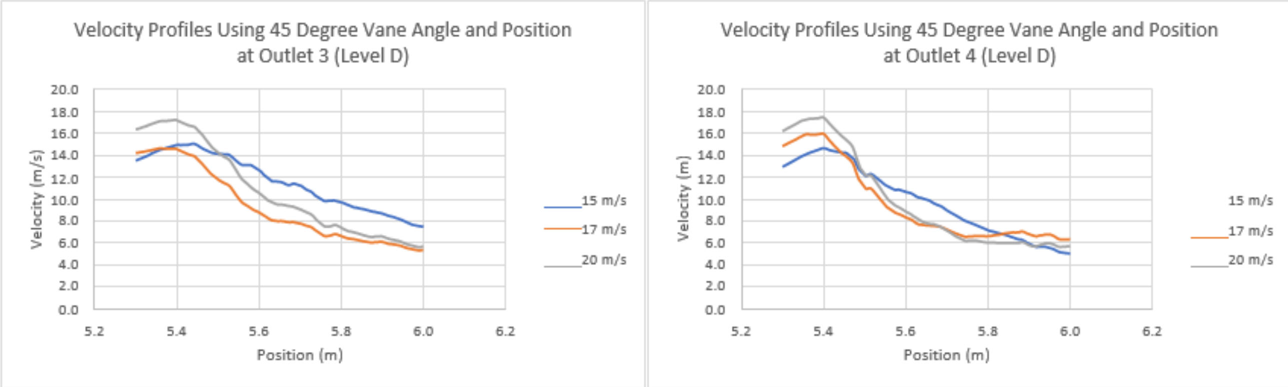

Fig. 17. Velocity profiles in coal pulveriser at outlet 3 and outlet 4 (level D) for various inlet velocities (45° vane angle)

From the graphs, it can be noted that higher inlet velocity contributes to the higher velocity at each level in the whole flow of the coal pulveriser. The velocity was mainly at the highest level when entering the air inlet (Level A) and reduced drastically when it reached Level B. Next, the velocity magnitude rose when it flowed to Level C and Level D but it decreased the velocity due to low pressure outside the coal pulveriser.

The flow of coal particles upward is dependent on axial velocity. Based on the result, it shows that higher velocity can be achieved when velocity at the air inlet increases. Besides, the highest axial velocity can transport large particles upward. The effect of different vane angles, like angles 45° and 60°, is it gives similar results.

Figures 18 to 21 show the velocity profiles of the whole area in the coal pulveriser for inlet velocities 15 m/s, 17 m/s and 20 m/s at Level A through Level D. The flow for a coal pulveriser with a vane angle of 60° flow is similar to coal pulveriser with vane angle 45°.

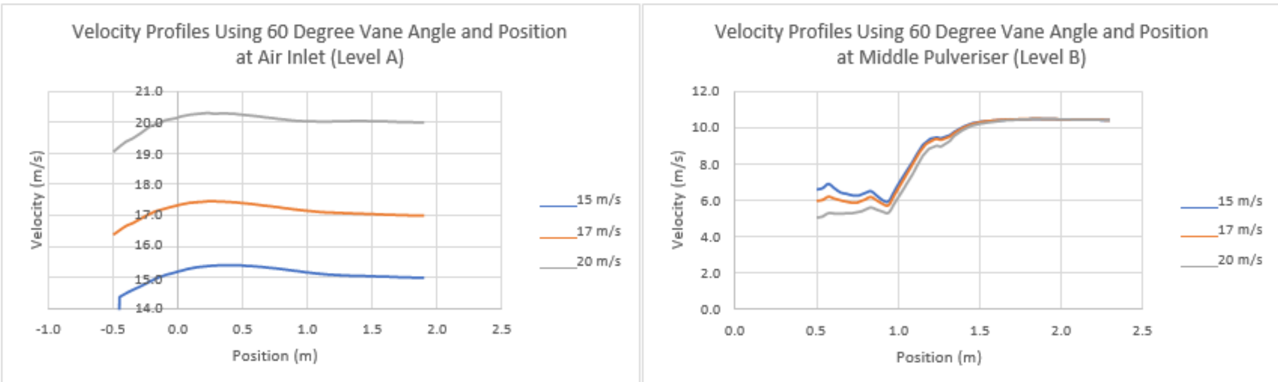

Fig. 18. Velocity profiles in coal pulveriser at air inlet (level A) and at middle pulveriser (level B) for various inlet velocities (60° vane angle)

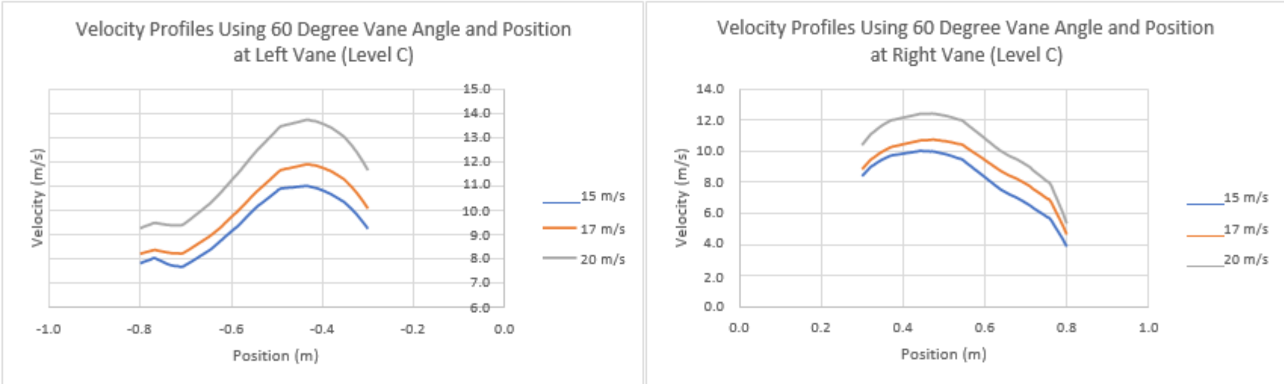

Fig. 19. Velocity profiles in coal pulveriser at left vane (level C) and right vane (level C) for various inlet velocities (60° vane angle)

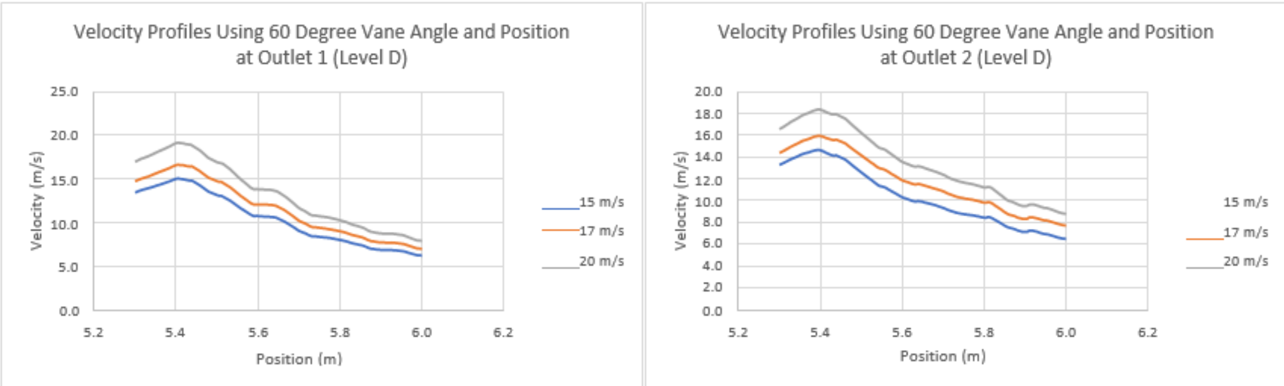

Fig. 20. Velocity profiles in coal pulveriser at outlet 1 (Level D) and outlet 2 (level D) for various inlet velocities (60° vane angle)

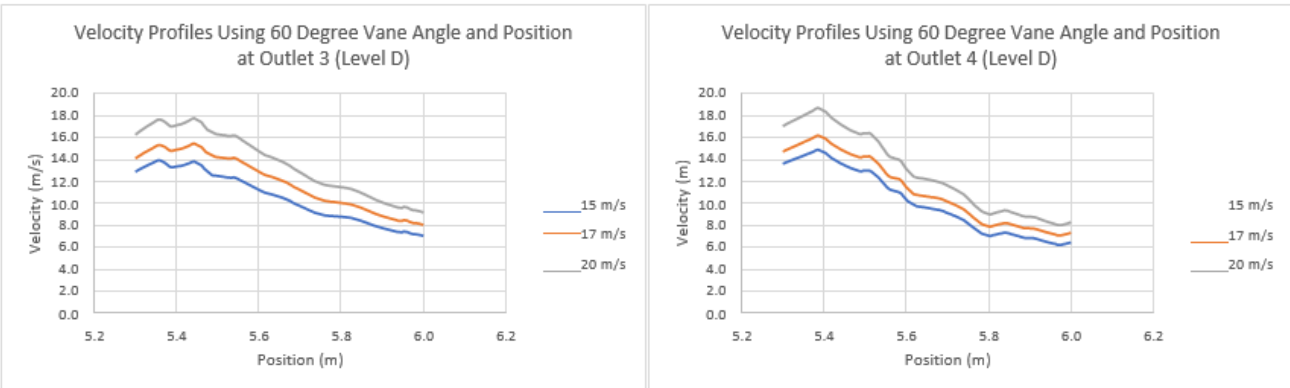

Fig. 21. Velocity profiles in coal pulveriser at outlet 3 (level D) and outlet 4 (level D) for various inlet velocities (60° vane angle)

3.5 Effect of Particle Flow with Different Vane Angle

Tables 3 and 4 show the particle escaped through an outlet of the coal pulveriser for both models. Based on the table, the particle escaped with three different particle sizes which are 50 µm, 75 µm and 100 µm for 60° vane angle recorded higher than 45° vane angle. The swirling velocity streamlines in the 60°-degree vane angle model influence the percentages of particle escaping which gives a smooth path for the air and coal that has been injected.

Table 3
The particle escaped for 45° vane angle

Particle size (µm)	Escaped	Escaped (%)
50	82	66.13
75	70	56.45
100	2	1.61

Table 4
The particle escaped for 60° vane angle

Particle Size (µm)	Escaped	Escaped (%)
50	86	69.35
75	74	59.68
100	3	2.41

4. Conclusions

In this study, Computational Fluid Dynamic was used to simulate the flow inside the coal pulveriser. This simulation takes advantage of ANSYS-Fluent 2021 R1. The simulation was successfully run, and the result was obtained. The CFD simulation coal pulveriser model highlights in this study are 45° vane angle and 60° vane angle.

Based on the study, it found that the motion for model 45° vane angle is unsteady flow while the motion for model 60° vane angle is a swirl. This happens due to the different angles of the vane. If the angle is small, the flow of fluid particles is not smooth while the large vane angle will produce better particle flow. Based on the result of particle escape from the outlet, the larger vane angle can escape more particles than the smaller vane angle. Furthermore, the velocity inlet at the air inlet (level A) of the 45° vane angle and 60° vane angle are the same but at the outlet, (level D) the recorded velocity is of different values and the 60° vane angle produced higher velocity value. This is because the pressure drop for the 60° vane angle is lower compared to the 45° vane angle. For the particle escaped in the outlet, the vane angle for the coal pulveriser model 60° recorded more particle escaped percentages for 50 µm and 75 µm particles while the coal pulveriser with a vane angle of 45° recorded more particle escaped for 100 µm particle size. Both pulveriser models are efficient and can facilitate the better process of coal from raw coal process until entering the boiler.

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