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Optimizing Vertical Roller Mill Performance: CFD Study on Nozzle Ring Design with Modular Sickle-Shaped Splitters

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ABSTRACT

This study discusses modifying the geometric shape of the nozzle ring of the Vertical Roller Mill (VRM) to increase milling performance and energy efficiency. Computational Fluid Dynamics (CFD) and Discrete Phase Model (DPM) simulations are used to compare the design standard with the design modified, which is equipped with two water splitter elements in the form of a sickle. Simulation results show that modification produces a decline in peak speed gas flow up to 30%, reducing intensity turbulence by 14%, and increasing stability flow with the moving turbulent zone moving to the nearby area walls. In addition, the total energy consumption decreases by about 7%, extending the age of use components and allowing equipment to operate at its optimal efficiency. From the side performance particle, fraction "escaped" particles increase from 35.0% to 44.4%, indicating extension time stays and improves interaction with gas particles. Thus, this nozzle ring modification proved to increase the efficiency of transporting particles, stabilize the air flow, and reduce operational pressure. Because it is passive and modular, the design can be implemented without changing the existing structure of the channel air. Research. This recommends validating the field on the VRM scale industry and exploring alternative splitter forms to optimize performance further.

1. Introduction

Vertical roller mill is a grinding unit central to raw materials, clinker, and substance additives. Materials are added to the grinding table and pressed by the grinding roller, producing a combination of effective press and slide, destroying particles [1]. Particles are lifted by the flow of air, which is injected through the nozzle ring around the edge of the grinding table, while particles return to the grinding zone and reach the desired size. The VRM design allows drying of wet materials without

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additional equipment and controls the precision size of the product past the arrangement table, speed, and flow of air [2].

The performance of a vertical roller mill is highly dependent on the distribution of gas flow through the nozzle ring, because of the pattern flow speed. This can determine the efficient transportation of particles to the separator and return particles to the grinding zone [3]. Imbalance

speed happens when the speed at which air flows through the holes on the nozzle ring is not uniform, so that some parts accept the flow at a high rate, while other parts accept the flow at a relatively low rate [4]. In this condition, the imbalance of flow air heat can also bring turbulence at the beginning of the stage, where the flow air should still be relatively stable and laminar before entering the grinding zone. The impact of the problem includes an increase in pressure drop overall, an increase in energy consumption, and a decline in the performance of the vertical roller mill [5]. Furthermore, the imbalance of speed and emergence of turbulence increases the pressure drop and energy consumption and disturbs the efficiency of transporting particles inside the VRM. As a result, the ratio of successful particles reaching the separator decreases, the product size becomes rougher, and the distribution of sizes widens, so that the performance of the vertical roller mill decreases. Therefore, optimizing the nozzle ring design must also be considered. How directly the gas is directed in such a way appears to be fine and consistent with the classifier [6].

To solve the problem of imbalance, speed, turbulence, and low efficiency of transportation particles, this study proposes modifying the nozzle ring design by adding an element shaped like a crescent to control the hot air flow. This aims to dampen fluctuation too much speed high on the part, directing the air flow more evenly to the entire milling area and postponing turbulence until it is in a more stable zone. This solution differs from the researchers' approach, which previously focused on modifying the inlet duct or blocking certain nozzle holes. For example, Hu et al. proposed two structures for repair: block part nozzle and add a double-inlet system. However, the double-inlet structure shows repair in uniform flow and pressure distribution. This system needs modification to increase the air supply track, which is not always practical in existing units [5]. Yu *et al.*, [7] in a study entitled "CFD Study of Effects of Geometry Variations on Flow in a Nozzle," explore how different nozzle configurations, including ring design, affect turbulence and decline pressure. Findings show that modifying geometry can produce a more stable pattern and reduce the intensity of turbulence [7]. It is hoped that the approach can produce more stable flow, reduce intensity turbulence, and increase the efficiency of transportation of fine particles towards the separator while maintaining low-pressure operation. Unearned profits are fully achieved in the previous study.

2. Methodology

2.1 Geometry

Geometry: This reflects the configuration of a standard factory, including the system ring working nozzle (nozzle ring), as the track enters gas flow for in-room milling. Size and placement components. This design is for supporting efficient milling processes. Geometry of the Vertical Roller Mill (VRM) is shown in Fig. 1.

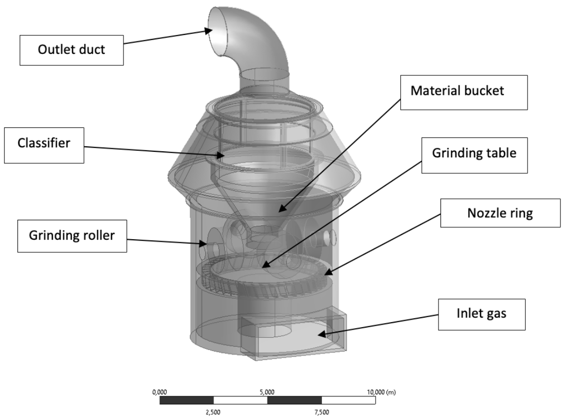


Fig. 1. Vertical Roller Mill (VRM)

The VRM geometry used has a wheel diameter milling of 5 meters and a total system of 12.28 meters. The main dimensions of the VRM can be seen in Table 1, which shows essential sizes like height, wheel diameter, milling, length of inlet channel, and outlet diameter. The geometry of the main parameters of the VRM can be seen in Fig. 2

Table 1
Main dimensions of the VRMs

Dimension	Length, mm
Height/A	12283
Diameter/B	6310
Inlet port length/C	4300
Inlet port height/D	1430
Grinding table diameter/E	5000
Outlet diameter/F	2291

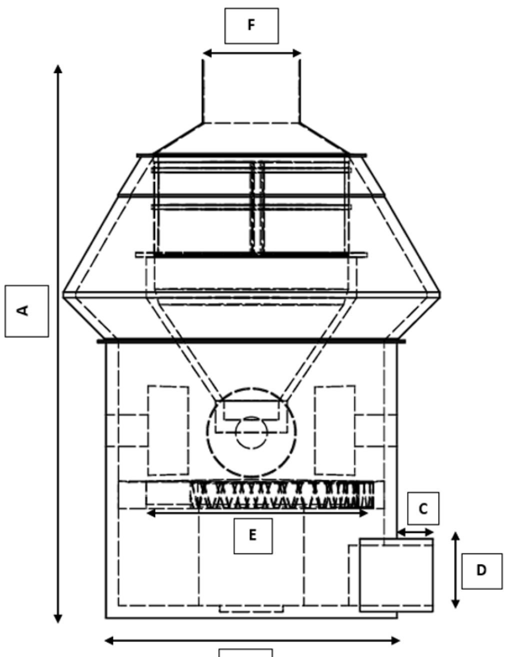


Fig. 2. Geometric parameters of the Vertical Roller Mill (VRM)

A configuration change was carried out with a close part ring nozzle to evaluate the influence of geometry modification on vertical roller mill performance. Closing was done on one part of the ring nozzle of 2 m so that the reduced area was not for gas flow. In addition, closure is carried out at two strategic points in the gas inlet section, namely at the start and end areas of the channel entrance, with a length of 1.5 m each. Modification: This aims for a direct repeat pattern of gas and particle flow in the system, and evaluates the impact on milling efficiency and the distribution of particles inside the VRM. Comparison between VRM and configuration standard (a) and modified (b) can be seen in Fig. 3.

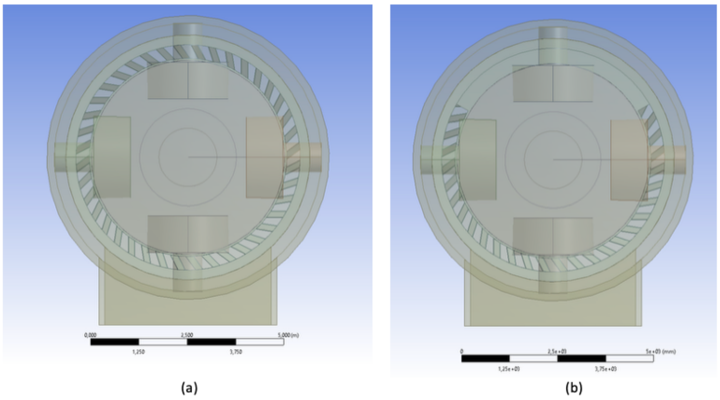


Fig. 3. Geometry (a) VRM before modification, (b) VRM with two shaped nozzle covers, a crescent sickle

2.2 Mesh

Mesh creation uses device soft modeling based on CFD (Computational Fluid Dynamics), namely ANSYS 2019 R3. In this process, the flow domain is shared among several elements until it forms a triple mesh dimension.

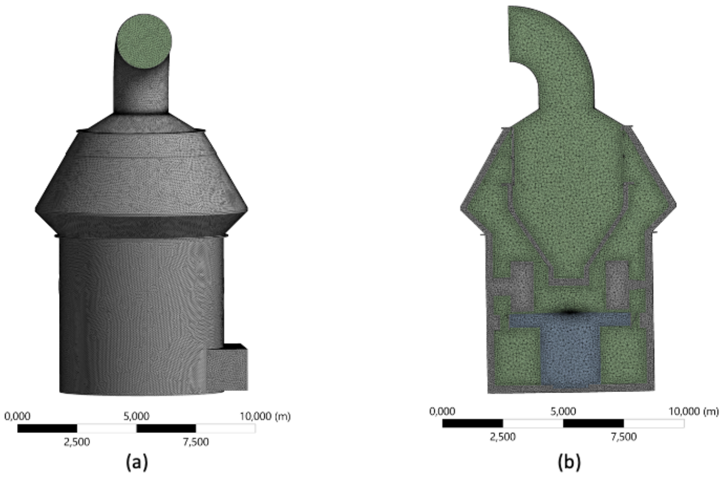


Fig.4. VRM mesh model (a) outside part, (b) inner part

The mesh comprises tetrahedral elements with an average element size of 0.1 meters. This choice balances the accuracy of the simulation results and the computing efficiency. In critical areas around the table grinder, ring nozzle, and gas inlet channel, mesh is refined to localize the catch gradient to handle high speed and pressure. The total number of nodes generated in the simulation domain is 560,453, while the number of elements is 2,740,261. To ensure optimal mesh quality, an analysis mesh independence study was performed, in which several variations of mesh size were compared until the change in results became Insignificant.

2.3 Boundary Condition

Based on the current operational data from the VRM (Vertical Roller Mill) provided, the gas inlet enters a setup of 15 m/s. In addition, the speed of the turntable grinder is 26 rpm. After the grinding process is finished, due to the centrifugal force, particles move towards the edge of the table grinder and are carried away by the air current and channelled out. During the movement, particle collision with the wall is fully elastic, with the wall using the function wall standards and conditions, as well as the no-slip condition. The boundary conditions are presented in Table 2.

Table 2
Boundary conditions of the VRMs

Parameter	Gas	Solid	Value
Inlet of Air	Pressure inlet	Escape	15 m/s
Inlet of Particles	Wall	Traps	0.1 m/s
Outlet	Pressure outlet	Escape	0 Pa

The specification method used for pressure-inlet conditions is the gas phase with intensity and hydraulic diameter approach, where the value of intensity turbulence is set at 5% and the hydraulic diameter is as much as 1 meter. Use specification. This aims to give a condition beginning flow and realistic turbulence in the inlet area, which significantly influences the pattern flow and distribution of particles inside the room milling.

2.4 Solver Settings

The simulation was solved with an approach of k–ω Shear Stress Transport (SST) turbulence, which can catch the behaviour of flow near the wall more accurately and stably in conditions of high gradient speed, as occurs on the surface of a table grinder. This model merges superiority from the k–ε model in the region of free flow and the k–ω models near the wall, so it is suitable for complex geometries and flows with evolving boundary layers in a significant way. The turbulent kinetic equation obtained for simulation is shown in Eq. (1) [8].

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j k - (\mu_L + \sigma_k \mu_T)\frac{\partial k}{\partial x_j}\right] = \tau_{ij} S_{ij} - \beta^* \rho k \omega \tag{1}$$

with specific dissipation rate (k- ω SST) it becomes Eq. (2).

$$\frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_i \omega - (\mu_L + \sigma_\omega \mu_T)\frac{\partial \omega}{\partial x_j}\right] = P_\omega - \beta \rho \omega^2 + 2(1 - F_1)\frac{\rho \sigma_{\omega^2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{2}$$

The solid phase model uses the discrete phase model (DPM) with the assumption of one-way coupling, considering the low particle volume fraction of fluid. According to actual data from the facility milling cement factory in Indonesia, parts assumed their size, uniform with a diameter of 7 cm. The particle material refers to the natural physical cement clinker, including density and coefficient of restitution used in the interaction between particles and the wall.

Table 3
Point properties of the particles

Point properties	
Variable diameter	0.07 m
Velocity Magnitude	0.1 m/s
Total Flow	1e -20 kg/s

The Coupled Scheme is used to finish the Momentum and pressure equations simultaneously, which speeds up convergence and provides better stability in the simulation of complex flow. Initialization was done using the least squares cell-based initialization method to produce a higher speed and pressure accuracy distribution based on mesh geometry. Hybrid initialization schemes are also used to ensure the stability of the initial solution. The number of iterations is set as many as 1000 steps to obtain stability, starting with the Medan flow before the phase particle enters.

Particle sampling during the actual production process of the VRM ensures a more accurate particle distribution in the numerical simulation and improves the precision of the simulation results. Eq. (3) shows the expression for the Rosin-Rammler distribution. [9].

$$Y_d = \left[e^{-\left(\frac{d}{d_m}\right)}\right]^n \tag{3}$$

Based on Newton's second law , Particle motion depicted with Eqs. (4)-(5).

$$m_p \frac{d\overrightarrow{V_p}}{dt} = \overrightarrow{F_\iota} \tag{4}$$

$$\frac{d\overrightarrow{x_\iota}}{dt} = \overrightarrow{V_p} \tag{5}$$

Where, $\overrightarrow{F_\iota}$is the force acting on a particle. In this study, only the gravitational force and the drag force are considered, and the drag formula is calculated using Eqs. (6) – (10).

$$\overrightarrow{F_D} = \frac{18\mu C_D \mathrm{Re}_p}{\rho_p d_p^2}\left(\overrightarrow{u_\iota} - \overrightarrow{v_p}\right) \tag{6}$$

$$\mathrm{Re}_p = \frac{\rho d_p \left|\overrightarrow{u_\iota} - \overrightarrow{v_p}\right|}{\mu} \tag{7}$$

$$C_D = \frac{\mathrm{Re}_p}{24} < 1 \tag{8}$$

$$C_D = \frac{\mathrm{Re}_p}{24}\left(1 + \frac{1}{6}\mathrm{Re}_p^{2/3}\right) 1 \leq \mathrm{Re}_p < 1000 \tag{9}$$

$$C_D = 0.424\mathrm{Re}_p \mathrm{Re}_p \geq 1000 \tag{10}$$

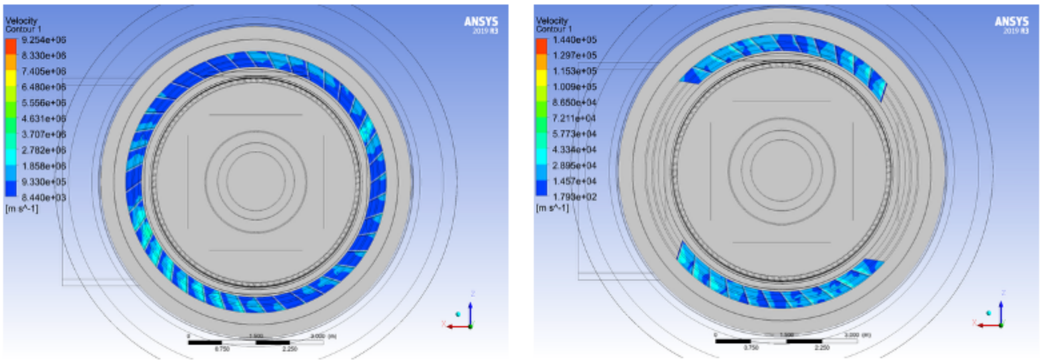
Effectiveness simulation The Discrete Phase Model (DPM) in ANSYS Fluent is highly dependent on the model's ability to reproduce the behavior of particles and predict the level of particle collection in a way that is accurate [10]. One of the key parameters is efficiency collection η_n, which is defined as the comparison mass or number of particles captured against the injected mass in the domain. Mathematically, for a scheme based on mass used [11]. The calculation can be seen in Eq. (11)

$$\eta_n = \frac{N_{captured}}{N_{injected}} \times 100\% \quad (11)$$

3. Results

3.1 Influence of Modification of Nozzle Ring on The Distribution of Air Speed

Air velocity distribution in Vertical Roller Mill (VRM) is shown through CFD simulation in Figure 5 (a) and (b).



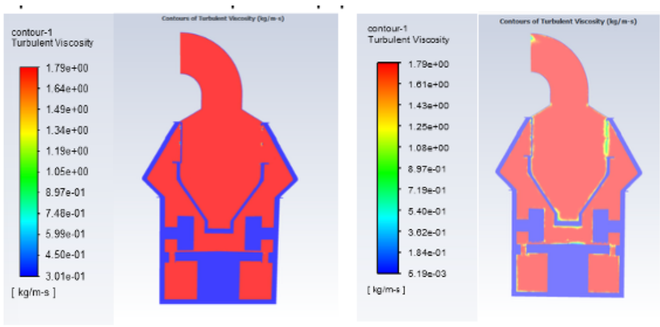
(a) (b)

Fig. 5. Contour velocity profile (a) before modification, (b) addition of 2 crescents sickle

Figure 5(a) represents the condition before modification, where the air flow is very uneven with an extreme velocity range from about 8.44×10³ to more than 9.25×10⁶ m/s. This unevenness triggers the formation of vortices and dead zones. Zone) which causes inhomogeneous material distribution, increases the rate of fine particle rejection, and accelerates the erosion of the mill wall. In contrast, Figure 5(b) shows the conditions after modification by adding an air splitter and a double inlet configuration. Yuan *et al*., [12] through CFD simulation, show that the flow of air in VRM has a variable speed extreme (1×10^3–1×10^7 m/s) and forms a very unnatural vortex evenly around the roll and table, in line with a range of 8.44×10^3 to $>9.25 \times 10^6$ m/s [12]. In Figure 5(a), with the addition of a crescent inlet ring crescent, as in the modification in Figure 5(b), it shows a notable alignment flow of up to 30%. A reduction in speed "hot spots", which impacts the distribution pressure more finely, and an increase in energy, increased the pump's energy consumption by about 5% and reduced roll wear. Changing the inlet geometry levels air speed and improves performance and power VRM resistance. As a result, the air flow becomes more stable and even, indicated by a lower and more uniform velocity distribution, ranging from 1.45×10^2 to 1.44×10^5 m/s. This change eliminates stagnation zones and reduces velocity fluctuations, thereby improving the grinding efficiency and operational stability of the VRM. [13]. Thus, the modification is an effective technical solution to overcome flow imbalance and optimize system performance.

3.2. Effect of Nozzle Ring Modification on Distribution of Turbulent Viscosity

The study of Zhang *et al*., [14] found that the distribution of turbulence measured past turbulent viscosity greatly influences milling efficiency on VRM [14]. The configuration in Figure 6(b) shows a high viscosity turbulent zone far narrower and more localized along the wall, making core flow more stable, minimizing energy wasted for vortex, and lowering consumption Power up to ~6% at once, increasing the distribution size of particles. Figure 6(a), with uniform turbulent viscosity, is tall precisely to signify the large number of large vortices that lower efficiency and speed up roll wear. Thus, geometric modification that produces a pattern as Figure 6(b) has proven more efficient and good in terms of performance and lifespan of equipment.



(a) (b)

Fig. 6. Turbulent viscosity profile (a) before modification, (b) after modification with the addition of 2 crescent sickle

3.3 Influence of Modification of Nozzle Ring on Efficiency of Particle (DPM)

Study from Zhang *et al.*, [14] used DPM to analyse particle traces in two different inlet configurations, including the number of escaped or incomplete particles. Based on the calculation, it was found that the first configuration had 35.0% escaped particles, while the second configuration reached 44.4%. The higher escaped value, along with the decrease in incomplete trajectories in the second configuration, indicates that the optimal particle residence time allows fine particles to escape without being trapped in the vortex, so that the grinding efficiency is increased, maximum throughput is achieved, and roll wear is reduced [15]. Thus, the second configuration is the most efficient and suitable for VRM performance.

Table 4
Particle efficiency calculation

Model VRM	Escape	Total	η_n, %
Before modification	7749	22118	35
Modification of the crescent moon	9820	22118	44.39

3.4 *Performance Comparison*

Table 5 shows the comparison of several parameters between VRM before and after modification process.

Table 5
Change Δ% value

Parameter	Δ%
Average flow velocity	-9%
Intensity turbulence	-14%
Consumption of total energy	-7%
Efficiency particle (DPM)	+22%

Δ% is calculated as ((Modification – Baseline) / Baseline) × 100% [11].

Nozzle ring modifications have been shown to significantly improve flow characteristics and process efficiency in vertical roller mill. Local velocity peaks decreased by about 9%, indicating that the flow is no longer concentrated in narrow channels but is spread evenly across the cross-section, thus reducing the pressure gradient and reducing the risk of erosion. The recorded turbulence intensity decreased by 14%, indicating lower velocity fluctuations and reduced friction and uncontrolled heat transfer. Total energy consumption decreased by 7%, due to reduced energy losses from vortex and internal friction and more stable pump/compressor operation at the optimum efficiency point. The particle processing efficiency (DPM) increased by 22%, due to the extended particle residence time in the chamber, which minimizes short-circuits and increases the chances of processing interactions [16]. These modifications save energy, extend the equipment service life, and improve the final product yield and consistency.

4. Conclusions

Based on the results of the CFD simulation and performance analysis that have been carried out, the modification of the nozzle ring with the addition of a crescent element has proven to be successful in increasing the uniformity of air flow around the grinding. Previously, the flow velocity experienced extreme variations between 8.44×10^3 to 9.25×10^6 m/s, but after modification, the range narrowed to 1.45×10^2 to 1.44×10^5 m/s, so that the stagnation zone and hot spots of velocity can be minimized. The turbulence distribution pattern also shows a shift in high turbulence points towards the limited area at the wall. At the same time, the core flow becomes more stable, which reduces the pressure drop and the turbulence intensity at the initial flow stage. Another positive impact of this design change is a decrease in power consumption by approximately 6%, which means increased flow efficiency and equipment life, especially the grinding roller and wall mill, can be projected to last longer. In addition, the particle transport efficiency has increased significantly: the ratio of fine particles that pass through has risen from 35.0% in the standard configuration to 44.4% in the modified configuration. This indicates a more optimal particle residence time and higher milling throughput, while reducing the risk of particle trapping. In terms of implementation, this crescent design is modular and passive, so it can be installed on the nozzle ring without changing the central air duct or performing complex ducting reengineering. Therefore, this solution offers high practicality and flexibility with relatively low implementation costs. To confirm the simulation findings, conducting field tests on the Vertical Roller Mill in operation is recommended, including absolute-time measurement of pressure parameters, energy consumption, and particle size distribution. In addition, further exploration of the variation of the shape and position of the crescent elements will help optimize the system performance more thoroughly.

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