Study on the Effect of Modifying the Calciner Geometry in Cement Plant

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Abstract. In a cement plant, **s**uspension preheater is used to raise temperature of a raw mix so that the mixing process results in a high degree of calcination. In this research project, we attempt to increase degree of calcination to reduce the load in the kiln by including the calciner suspension pre-heater. This project focus on a suspension preheater system with a separate line calciner at cement plant with capacity of 5000 ton per day. Then the calciner will be modified its length. Computational fluid dynamics method was chosen to simulate the performance of the calciner. The results show that the modified calciner can increases the degree of calcination and improves the heat transfer rate. This lead to the decrease of temperature output of the top cyclone and thus reducing the heat consumption. Which such efficiency, the modification design opens possibility to increase the production capacity while maintaining the outlet temperature of the top cyclone.

Keywords: *calciner, cement plant, CFD, modification, suspension preheater*

1 Introduction

Indonesian government is now focusing on economic development by implementing The Masterplan for the Acceleration and Expansion of Economic Development of Indonesia (MP3EI). The main program of this masterplan includes many projects that are associated with infrastructure development [1]. Due to the high amount of infrastructure projects, the demand for cement is also projected to get higher. To fulfill this, cement plants are trying to increase their production. The cement sub-sector itself consume 12-15% of total industrial energy use [2,3]. One way to increase production capacity is by increasing the effectiveness of the equipment. It can be done by either doing maintenance or modifying the equipment so that it can maintain or improve its efficiency [2].

One of the equipment in the cement plant is suspension preheater (SP), which is used to heating up the raw material before continuing the burning process in the kiln. During the heating up process, the raw mix material is heated so that the

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moisture content evaporates at temperatures up to 500℃, and calcination process begins at 800℃. This process can be categorized as a key process in cement manufacturing where it takes about 25% of the energy consumed in the process [3,4].

In the suspension preheater with calciner, there is an additional fuel combustion where it transfers a part of the kiln heating load to a calcining vessel, where the raw mix undergoes a calcination process to a level of 80%-90%. The advantage of using a calciner is it could reduce heat load and diameter of the kiln, low-quality fuel can be used, consumption of refractory in the kiln can be reduced, the lifetime gets extended, and NO_x emission is considerably low since combustion happened in a low-temperature [5].

Several studies haves focused on the calcination characteristics. Fidaros, et al. [5] in their paper proposed a numerical model for the flow and transport process of a calciner. The model has successfully modeled an industrial calciner and could be used in predicting its process parameter. Mujumdar et al. [6] proposed more integrated modeling of a whole process from pre-heater up to clinker cooler. This model was used to predict kiln properties, such as maximum temperature and flame zone for coals which will help in developing and understanding of clinker formation. Mikulčić et al. [7] studied the thermo-chemical process that occurred inside calciner. The result can be used to understand the mixing reaction better and to optimize the burning process. Another study regarding thermal reaction has also been proposed by Tsamatsoulis [8] where the effect of fuel’s feed rate on the outlet temperature of calciner is observed. This study has successfully evaluated dynamic parameters of fuel that could be used in regulating the tuning process. Several modeling research also focused on emission effects from the cement production process [9,10]. The proposed model provides data of emission production and helps in determining an emission reduction plan for the plant.

Most of the previous researches were focused on developing a better understanding of a clinker production process. However, there are only limitedresearch that focused on optimizing the calciner geometry. Therefore, in the current research, the effect of modifying the calciner geometry will be analyzed using numerical method. The model of the heat transfer and calcination process in the first developed as a reference. Then, the model for a a modified design with a higher height will be developed and compare with the reference. The parameters to be compared include the calcination percentage, pressure, and temperature profile. The outcome of this research can be used as a reference for modifying the current cement plant and can help to improve its production while keeping the process efficiency.

2 Research Method and Methodology

This current research will focus on the CFD simulation of performance of two model calciners. The calciner model is taken from a cement plant with a capacity of 5000 ton per day (TPD) clinker with suspension preheater consists of two different cyclone configuration, in-line and separated line with a calciner attached in the end part as shown in Figure 1. The subject of study includes cyclone A4 and SLC calciner.

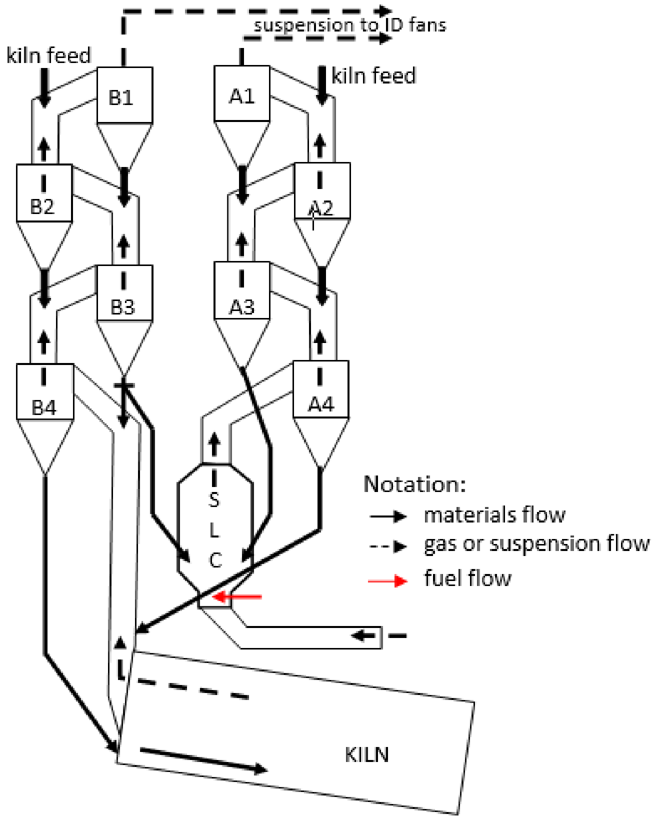


Figure 1 Schematic diagram of suspension preheater system with calciner

The combustion and calcination process performance of both existing and modified designs will be compared. First, we developed a model for the existing plant and ensured that the model correctly predicted the existing operating parameters. Then model will be modified by changing the dimensions of the calciner while keeping the operating conditions unchanged. The simulation method was carried out using FLUENT to solve all necessary flow, heat, mass transfers, and chemical reaction model.

The activities of the research is shown by the flowchart in Figure 2.

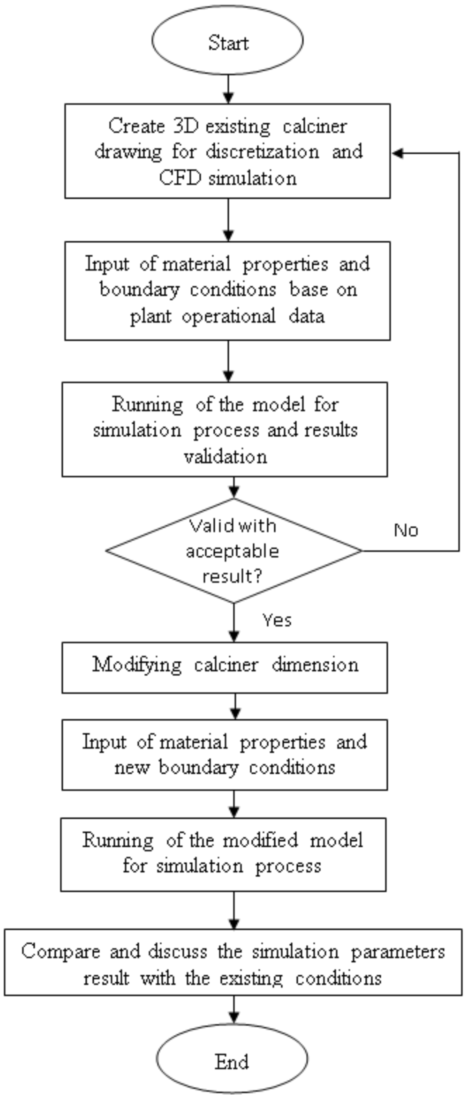


Figure 2 Flowchart of the CFD simulation process

2.1 Preheating Process

Preheater consisted of a series of cyclones connected by a duct, where the raw material is heated before entering the next process, clinker formation, and cooling, which takes place in the kiln and clinker cooler. The raw mix material is heated so that the moisture content evaporates at a temperature around 500ºC and the calcination process begins.

Calcination is an endothermic reaction, where raw mix which consists of calcium carbonate decomposed into calcium oxide, magnesium oxide, and CO_2 as a byproduct as represented in Equation (1).

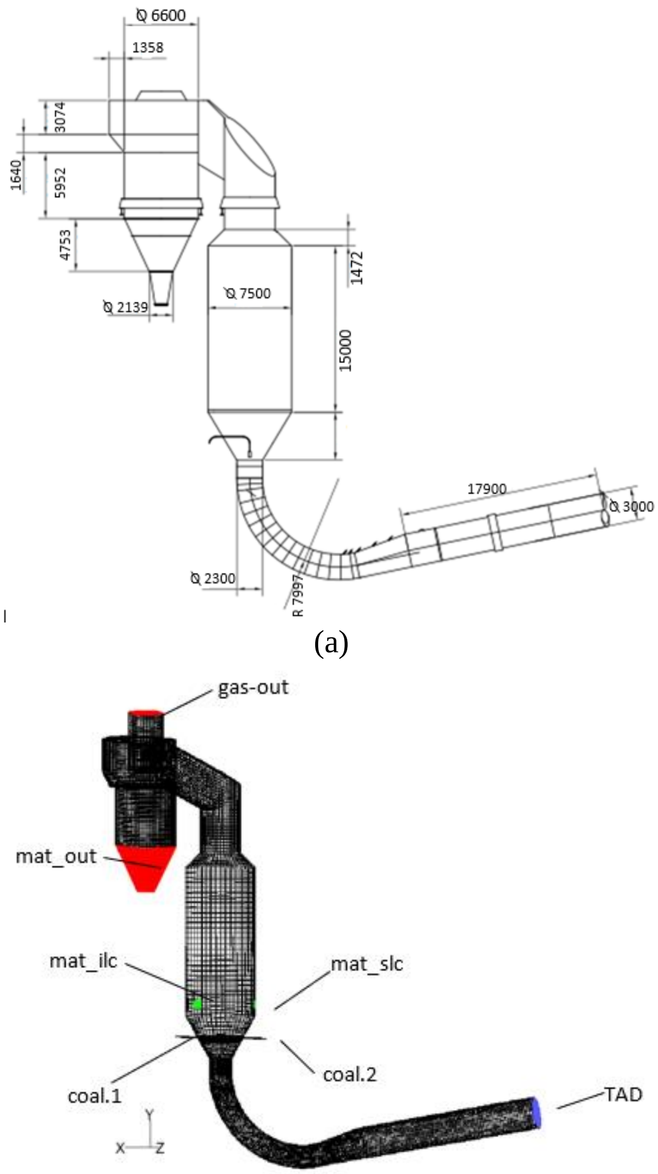
$$CaCO_{3\,(s)} + MgCO_{3\,(s)} + E_{cal} \rightarrow CaO_{(s)} + MgO_{(s)} + 2CO_{2(g)} \quad (1)$$

Inside the calciner, fuel is added which will burn with hot recovery air of the clinker cooling process in the cooler. The heat from this combustion is used for the raw mix calcination process until 80 to 90% of them is decomposed into CaO and CO_2. With the presence of a calciner, the heat load for the calcination process in the kiln is greatly reduced so that the dominant process in the kiln remains clinkering, sintering, and cooling. The other advantage of using calciner is it can use lower-quality fuel because the calcination process does not require temperatures as high as in the kiln. Another consequence due to reduced heat load in the kiln is the age of the refractory life will increase and the consumption will be less. Additionally, the NO_x emission will be very low due to combustion happen in low temperatures.

2.2 Numerical Simulation

A numerical simulation was being taken by computational fluid dynamics techniques using FLUENT software. The dimension and discretization of the existing calciner are shown in Figure 3. The entire model consists of the last stage cyclone A4, calciner, and outlet duct. On the bottom part of the calciner, there are each of the two places with a symmetrical position to enter the fuel and raw mix material. The tertiary air enters from the bottom of calciner through 3 m diameter tertiary air duct (TAD).

The simulation process is started with a 3D model drawing from the existing calciner design. The model then being discretized which divides the geometric model into the volume element. The mesh used for the model consists of 88.8% hexa-hedron elements and 11.2% t-grid elements. The quality of the mesh is then checked using skewness and volume change criteria. The elements were made smaller with equisized skew more than 0.85, and no element with size change more than 2. After the quality is considered good, the boundary condition of the system can be introduced. Figure 3 shows the dimension, meshing and all of the boundary condition for simulation. The existing model needed to be validated to make sure the process simulation results can represent the actual calciner operation. Validation for the existing model is conducted by using temperature outlet from cyclone A4 and percentage degree of calcination which derived from operation data of the plant. The value used for validation is 810℃ for outlet temperature and 70% for percentage degree of calcination.



(b)

Figure 3 Dimension (a) and dicretization (b) of the studied calciner model

2.2.1 Mathematical Models

All the heat and mass transfer as well as chemical reaction models are solved numerically using FLUENT. The general equations such as conservation of mass momentum and energy, combined with the influence of the turbulence model are already provided in the software. However, some equations are still needed to be matched the process that occurs in the calciner. For example, the k-ω turbulence model is used to turbulence model for this case because this model can work fine for low Reynolds number, and suitable for low-speed flow in the calciner [7]. Moreover, since the model includes coal combustion and calcination process, the combustion model is also used for this specific case.

Turbulence k- ω Model

The turbulence model used for this work is k- ω turbulence model. k - ω can be stated as a transport equation for turbulence kinetic energy (k) and specific rate of dissipation (ω), as represented in the following equations [11].

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \quad (2)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + S_\omega \quad (3)$$

Where G_k represents the generation of k due to mean velocity gradients and G_ω represents the generation of ω. ω is the ratio of turbulence kinetic energi (k) and turbulence dissipation rate (ε), while Γ_k and Γ_ω represent the effective diffusivity of k and ω. S_k and S_ω are the user-defined source terms, while Y_k and Y_ω represent the dissipation of k and ω due to turbulence.

Coal Combustion Models

The combustion model used in the current research includes the devolatilization model and combustion char component using a limited diffusion rate, as represented in the Equations (4) to (6) [11].

$$\frac{m_v(t)}{m_{p0} - m_a} = \int_0^t (\alpha_1 R_1 + \alpha_2 R_2) exp\left(-\int_0^t (R_1 + R_2) dt\right) dt \quad (4)$$

$$R_1 = A_1 \exp\left(-E_1/RT_p\right) \quad (5)$$

$$R_2 = A_2 \exp\left(-E_2/RT_p\right) \quad (6)$$

The model used in the coal devolatilization process is a model with two competing rates where the devolatilization rate is a function of the two yield factors α_1 and α_2. In the equations above, $m_v(t)$ and $m_{p0}(t)$ are the mass of reacting volatile matter and the initial mass of the coal particles. While R_1 and R_2 are the reaction rate and kinetic rate with A_1, A_2, E_1, and E_2 respectively being the rate constant parameters of the reaction kinetics.

The combustion char process happened after the devolatilization process, with a diffusion-limited rate. Heat transfer during the combustion process of coal particles is expressed by the energy balance equation for the particles such as Equation (7).

$$m_p c_p \frac{dT_p}{dt} = hA_p\left(T_\infty - T_p\right) - f_h\left(\frac{dm_p}{dt}\right)H_{reac} + A_p\varepsilon_p\sigma(\theta_R^4 - T_p^4) \quad (7)$$

Calcination Process

For solid particle reactions, the combustion model can be used ignoring the devolatilization process and considering the char fraction as the percentage of C in $CaCO_3$. The calcination process then approached by combusting particle reaction, which can be written as Equation (8).

$$Char_{(s)} + S_bO_{2(g)} \rightarrow Product_{(s)} \quad (8)$$

S_b is the mass ratio of oxidant per unit mass of char and is referred to as the burnout stoichiometric ratio. The decomposition process of char component is modeled with kinetics/diffusion-limited rate. The reaction rate is dominantly determined by oxidant diffusion to the particle surface and kinetic rate. FLUENT used Baum-Street and Field model as shown in the Equation (9), to formulate the reaction rate R_1 [11].

$$R_1 = C_1 \left(\frac{[(T_p - T_\infty)/2]^{0.75}}{D_p}\right) \quad (9)$$

with kinetic rate R_2 is formulated by

$$R_2 = C_2 \exp\left(-\frac{E}{RT_p}\right) \quad (10)$$

where C_1 is a mass diffusion-limited rate constant and C_2 is kinetics limited rate pre-exponential. C_2 shows characteristics of limestone which can vary between different sources and affect the percentage degree of calcination.

2.3 Geometric Modification and Simulation

2.3.1 Existing Calciner Design

The model of existing calciner consists of a cylinder with 7.5 m diameter and 15 m height. The upper part of the calciner is connected to a cyclone separator A4 by riser duct while the lower part is connected to a tertiary air duct (TAD) which has a diameter of 3 m and length of 17.9 m.

The model has three kinds of inlets at the bottom part of the calciner and two types of outlets at the cyclone A4 for material passed and hot gas exit as mentioned in Figure 3(a). Raw-mix comes from two sources line, one from SLC line cyclone A3 and the other from kiln line cyclone B3 while the coal is fed face to face from lower conus part of calciner through 0.3 m diameter pipe. All the mass flowrate and initial temperatures used in the model are summarized in Table 1.

Table 1 Simulation parameters values

Mass flow	Quantity (kg/s)	Temperature (^oC)
Raw material from cyclone A3	44.23	720
Raw material from cyclone B3	53.74	730
Tertiary air from clinker cooler	51.50	700
Fuel (vapor included)	5.00	60
Fuel conveying air and false air	0.76	60

2.3.2 A Modified Calciner Design

A modification was performed by changing the height of the existing calciner cylinder body. The bottom of the existing cylinder is increased by 2.5 m so that the total length of the cylinder becomes 17.5 m.

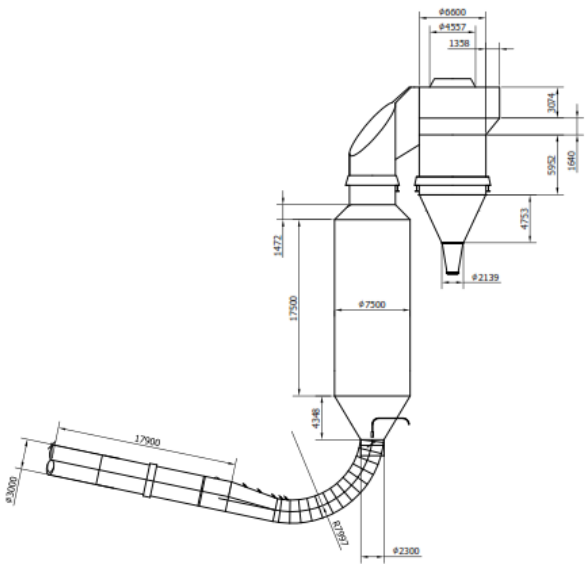


Figure 4 Modified calciner dimension

It can be done by lowering the duct of the conventional design. The drawing of modified design is shown in Figure 4. Except for the calciner height, the other operating parameters remained the same. By keeping the parameter unchanged, the result is expected to show only the effect of height modification. Since the height is added, the degree of calcination is expected to increase since the rawmix material spends more time inside calciner.

3 Result and Discussion

Some of the parameters to be compared for this research include temperature, pressure, and percentage degree of calcination are summarized in Table 2. The temperature of cyclone inlet from calciner is lower with a 2% difference. Meanwhile, the pressure loss in the duct, calciner and cyclone A4 decreases while the percentage degree of calcination increases to up 5.32% with a better heat transfer rate from the combustion gas to particles.

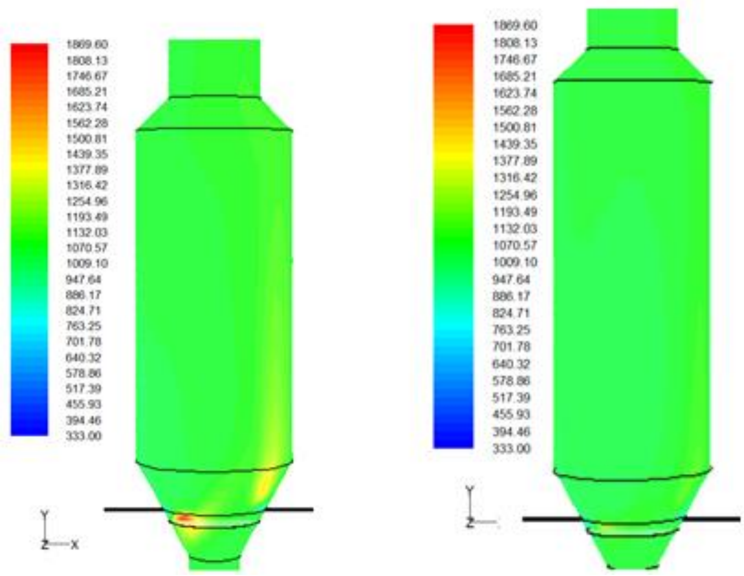
Table 2 Parameter comparison existing and modified calciners

Parameter		Existing Calciner	Modified Calciner	Difference
Temperature (°C)	Cyclone A4 Inlet	791	772	-2%
	Cyclone A4 Outlet	779	759	-2%
Pressure Loss (Pa)	duct	378	329	-12%
	Calciner	135	143	+5%
	Cyclone A4	239	217	-9%
Percentage degree of calcination (%)		71	76.32	+5.32
Total heat transfered from gas to particles (kW)		50574	55707	10.15%

3.1 Temperature Distribution Analysis

Combustion of fuel with hot air from clinker cooler can reach a temperature of 1750°C at some point within the lower conus part of the calciner. The heat produced by this combustion process will be used as a source for the calcination process. The temperature distributions for the two models are presented in Figure 5. The outlet temperature of an existing calciner shows a temperature of 795°C. There are still hotspots at several point indicating unabsorbed heat by the material. A different result is shown from the modified design where the temperature distribution has not shown any hotspots in the lower conus part. Furthermore, the temperature of the modified calciner shows a slightly lower value of 790°C.

In the modified model, it can be seen that as the height of the calciner increases, the hot gas reach the combustion gas faster. This affects the calcination process and gives a uniform heat absorption to the raw material. While in the existing model, the heat produced is not absorbed directly by the raw material marked by an increase of the temperature in the calciner body. As the height of the calciner increases, the particle spends more time and the process of heat absorption for calcination process also increasing. The total rate of heat transfer received by rawmix particles increased from 50574 kW to 55707 kW (more than 10%) as mentioned in Table 2.



(a) (b)

Figure 5 Temperature distribution of calciner a). Existing b). Modified

3.2 Pressure Loss

Pressure distribution analysis can be divided into three different zones, duct (zone A), calciner (zone B), and cyclone (zone C). The pressure difference of each zone is shown as the difference between the pressure at reference and the calculated area. The outlet of the cyclone is picked as the reference with 0 Pa. The zone division for pressure distribution can be shown in Figure 6 while the comparison of gas pressure distribution inside the calciner between the existing design and the modified one is shown in Figure 7. The inlet side of the duct in the modified design shows a pressure of 546 Pa while the outlet shows 217 Pa. The decrease in pressure is caused by pressure loss due to the 90° bending, diameter reducer, and surface condition. While the existing design shows a pressure of 636 Pa for the inlet and 374 at the outlet. On the calciner body of the existing calciner, the outlet side shows a pressure of 239 Pa. However, compared to existing, modified calciner gives a lower value in the outlet side, 217 Pa, since the calciner body is higher.

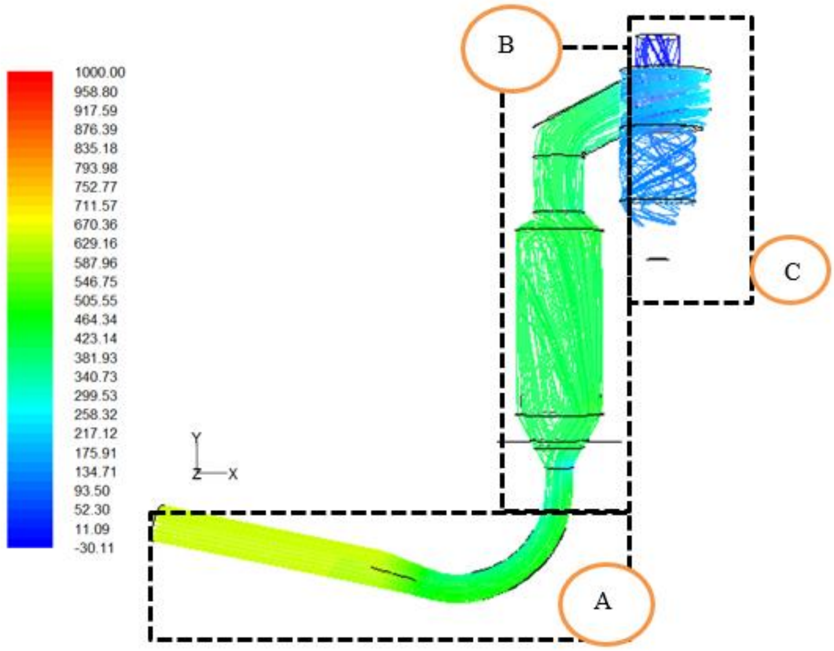
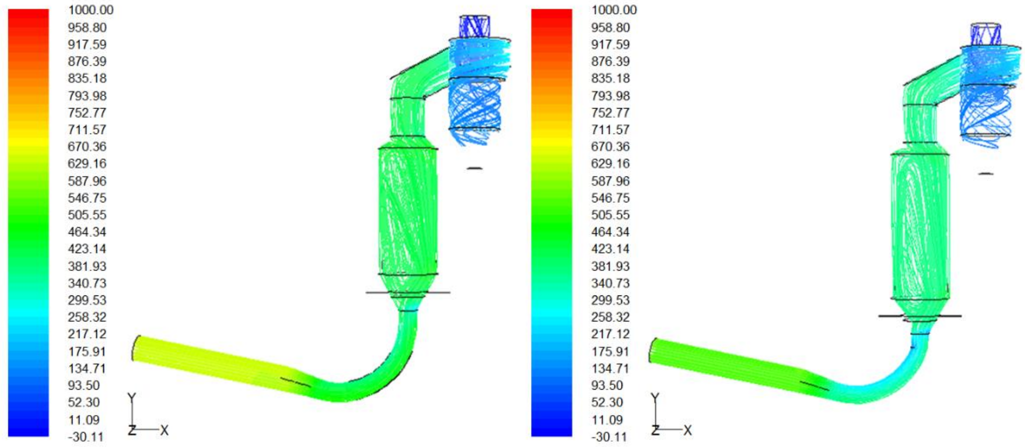


Figure 6 Zone division for pressure distribution A: duct, B: Calciner, and C: Cyclone



(a) (b)

Figure 7 Pressure distribution (Pa): a). Existing Calciner b). Modified Calciner

The difference of pressure between inlet and outlet is very small since the geometry of the calciner consists of a cylinder without bend and has bigger diameter which influences the pressure drop that happened in the calciner. The total pressure loss on the existing calciner system (752 Pa) is higher than the modified calciner (689 Pa). This will be beneficial because it will reduce the power of the fan used to circulate gas. The biggest difference between the two occurs in the duct (zone A), which is about 12%.

3.3 Percentage Degree of Calcination

Using the combustion particle approach, the percentage degree of calcination can be predicted by evaluating char content in the rawmix material. There are two rawmix materials injected from two different sources with two different mass flows. The existing design shows a calcination percentage of 71%. While the modified design shows a calcination percentage of 76.32%. The percentage degree of calcination in the modified calciner shows an increase of 5.32 points.

The increasing value of percentage degree of calcination corresponds to the modification of height since higher height makes raw particle has slower settling time in the calciner. The more time a raw material spends in the calciner means the higher chance of heat absorption. The increase of percentage degree of calcination fits with the heat absorbed by rawmix. The increase in the percentage degree of calcination brings more energy to the system since the process is endothermic. Energy absorbed by the calcination process, however, can also be used to add more rawmix mass flow to the calciner so that with the similar percentage degree of calcination target, the mass flow of rawmix can be increased. This gives an opportunity to increase clinker production. For the purpose of calculating the approximate increase in the raw mix mass rate that can be fed into the system, the heat value of the calcination process can be shown in FLUENT by using the heat of reaction for burnout parameter. Assuming the calcination percentage target is maintained at 71% as the existing design, with more energy coming from the process, the raw material can be increased to 105.31 kg/s from 97.97 kg/s previously.

4 Conclusion

The results showed that change of height in calciner contribute to better performance of the whole preheater, with an increase in the calcination process of 5.32 points from 71% to 76.32%. The value of heat absorbed by raw mix also shown an increase from 50574 kW to 55707 kW. This result is followed by a decrease in cyclone temperature and a pressure loss in duct and cyclone zone.

The pressure loss in the calciner has been increased although the value is very small. Overall, the decrease in temperature and pressure loss of modified design are still tolerable since the drop are very marginal and not affecting the subsequent process. Moreover, with taller cylinder body gives a better heat transfer for the material. While the modification affects the calcination percentage, the energy resulted from the process can also be used to increase the total raw material being processed. If the calcination percentage is set at the same value, the calciner can process up to 105.31 kg/s of rawmix materials, which means that an increase in production of 7.5% can be expected.

Finally, the change in calciner cylinder body has been proven to be beneficial for the cement plant and can be implemented in the existing plant. However, a more comprehensive review for the design needs to be implemented in terms of environmental effect, structural analysis, and financial aspect.

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