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INVESTIGATION OF THE PARTICLE MOVEMENT IN ROTARY KILN

MASTER’S THESIS

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Annotation - English: In this work, an investigation of what is a rotary kiln, how does it work, its application on the production of expanded clay pebbles and possible simulation methods using Ansys Fluent was done.

Keywords: Rotary Kiln, Heat Transfer, Particle Motion, Mean Residence Time, Response Angle, Fluent, DEM, DDPM, DPM, Rotary Drum, Kiln, Expanded Ceramic Pebbles.

Statement

I confirm that the diploma (Master’s) work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of the documents and literature.

In Prague …………………………………

José Renato Ronzón Tirado

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To my family, Hanka and all the close people that have supported and guided me throughout all these years.

Abstract

This work is study of what a rotary kiln is and its applications for creating expanded ceramics, for which, a brief discussion of what is a rotary kiln, what is clay and ceramics, heat transfer inside the kiln, the movement of the particles inside the kiln and simulation methods on ANSYS are exposed. Four simulations were performed, two using a smooth kiln but with different simulation techniques, and two using inserts inside the kiln to disrupt the flow of material along the kiln. A comparison in between the expected values for residence time between published formulas and the simulations was done as well as an analysis between the particle size and the residence time. For this work, ANSYS 16.2, Inventor 2015, EasyFit, and Microsoft Office software were used, and a brief guide of the process followed by the software setting, running and data analysis is presented for each of the simulations.

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1. Introduction

The aim of this work is to describe what is rotary kiln, what are the main principles acting on it, to describe clay and its properties, to examine a case of a ceramic aggregate production process that uses a rotary kiln, as well as to find a simulation model for the movement of the granular feed inside the kiln, using the software Fluent 16.2 with student license. The aim is also to suggest an alternative internal construction for the kiln and compare the simulations among themselves and the results of analytical solutions.

Due to the rarity of this equipment and the limited access to information about them, few variables will be given for the modeling of the kiln. These variables are - diameter, length, revolution speed, and inclination angle of the kiln, velocity of the countercurrent flow of air, mass flow rate, density and diameter of the particles of the feed. These variables will be used to obtain the mean residence time and dynamic response angle of the feed inside the kiln.

2. Literature Research – Particle Movement

In order to make necessary research to find what were the last ideas of how to approach this kind of problems and how to solve it, the tools provided by the university were used, more specifically the academic search engine SUMMON, found on the website of the library of the university:

https://knihovna.cvut.cz/katalogy-a-databaze/hledat-v/vyhledavac-summon

All the sources, articles and books, for this master ‘s thesis were retrieved from this source.

Many possible sources were read, but only following articles and books were selected for their quality and content. The Selected ones are summarized on the next pages.

2.1 Peray residence time

In the book “The Rotary Cement Kiln” written by Kurt E. Peray, published in the year 1972, [9] the mean residence time and percentage of loading was discoursed. As the name of the book indicates, this relation was developed from the study of the behavior of particles of cement and other dust like particles inside a smooth rotary kiln.

As it is stated in the book, the suggested formula is only a reasonable approximation, or first approach to predict the behavior of the kiln feed under normal operating conditions, no dams or internal constructions. The author also suggests that the range of the dynamic response angle of the feedstock inside the kiln may vary between 20 and 50 degrees and considers normal angles from 35 to 45 degrees for dust like particles according to their properties.

The proposed formula on the page 176 is the following one [9]:

$$\tau = \frac{CL}{NsD} \qquad (1)$$

In which

τ is the residence time in minutes

L is the length of the kiln in meters

N is the angular velocity of the kiln in revolutions per hour

s is the slope of the kiln ($^{m}/_{m}$)

D is the diameter of the kiln in meters

$$C = 1.77\sqrt{\xi} \qquad (2)$$

When the Dynamic response angle ξ is not known, the variable C takes the value of 11.4

The book also proposes a formula to calculate the percentage of loading of the kiln and recommends the use of it as a quick way to estimate the depth of the feed bed inside the kiln, and surface of the feed exposed to the interior of the kiln or in other words the chord length generated in a cross section of the kiln.

$$\% \, Loading = \frac{\frac{69.444wf}{\rho}}{A\left(\frac{L}{\tau}\right)} \tag{3}$$

Where; w is the kiln output in metric tons per day, f is the feed factor $\left(\frac{kg \, Feed}{kg \, Clinker}\right)$, ρ is the density of the feed, L is the length of it in meters, τ the residence time and A is the cross section area of the kiln in m^2

2.2 Boateng residence time

In the book “Rotary Kilns” written by A. A. Boateng, published in the year 2008 [3], the mean residence time, Froude number and cascades per kiln rotation among other related topics are discussed. This is one of the most popular publications about rotary kilns due to the fact that that it is widely quoted in many articles and its proposed formula for residence time is used as base for others.

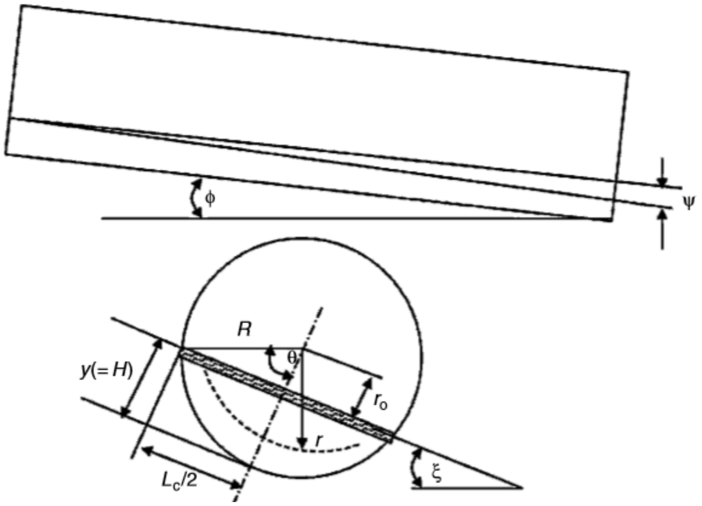


Figure 1; Rotary kiln geometry [3].

This book is a complete introduction and guide to the rotary kilns; it goes from an introduction to the equipment, history, geometrical description, main variables, momentum and heat transfer phenomena of the feed and burner of gas inside the kiln.

The following formula is presented to describe the mean residence time.

$$\tau = \frac{0.23L}{sN^{0.9}D} \pm \frac{BLG}{F} \qquad (4)$$

Where

τ Is the residence time in minutes

s Is the slope $\left({}^{ft}/_{ft}\right)$

N is the revolutions per minute

G is the freeboard gas velocity $\left(\frac{lb}{hr\,ft^2}\right)$

F is the feed $\left(\frac{lb}{hr\,ft^2}\right)$

B is a constant that depends on the material size

$$B = sd_p^{-0.5} \qquad (5)$$

d_p Is the particle diameter

It is also important to remark that the + symbol in the equation applies when the flow of air and feed is concurrent and – when the flow air and feed is countercurrent.

2.2.1Froude number

The Froude number helps to identify what kind of motion is doing the feed in the transverse plane of the kiln, this movements can be classified in six groups: Slipping, Slumping, Rolling, Cascading, Cataracting and centrifuging.

$$Fr = \frac{\omega^2 R}{g} \qquad (6)$$

Where ω is the angular velocity $\left({}^{1}/_{s}\right)$, R is the kiln radius in meters and g is the gravity.

The proposed formula to obtain the Froude number does not consider the particle diameter or other physical properties such as density, viscosities and friction in between particle-particle and particle-wall. As it is common in the rotary kiln description formulas; the complexity of the geometries and wide variety of feeds makes the postulation of universal formula that applies for all the cases almost impossible, in exchange there are many formulas that work as first approximation of what can be expected, for better accuracy it is necessary to run experiments or search for a formula optimized for the kind of geometry, feeds and operational parameters of each specific case.

As it was mentioned, the six ranges of the Froude number defined in the book that match with the kind of transversal movement are:

Mode	Fr
Slipping	$Fr < 1.0 \times 10^{-5}$
Slumping	$1.0 \times 10^{-5} < Fr < 0.3 \times 10^{-3}$
Rolling	$0.3 \times 10^{-3} < Fr < 0.2 \times 10^{-1}$
Cascading	$0.4 \times 10^{-1} < Fr < 0.8 \times 10^{-1}$
Cataracting	$0.9 \times 10^{-1} < Fr < 1.0$
Centrifuging	$Fr > 1.0$

Figure 2; Froude number meaning [3].

And as presented in the book, each region would look like the following:

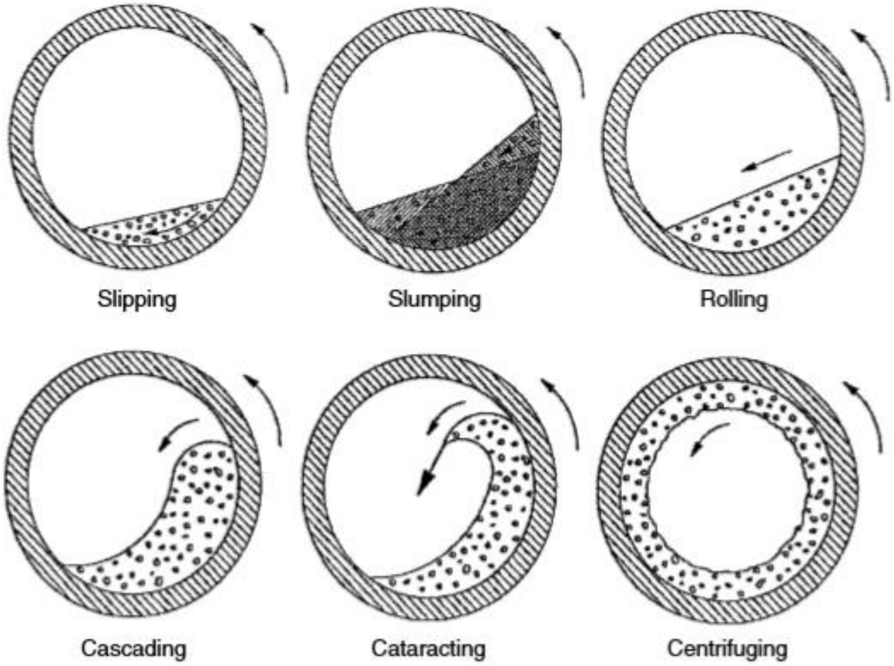


Figure 3; Froude number meaning diagrams. [3]

Finally, a mapping of the bed behavior on four operational parameters presented

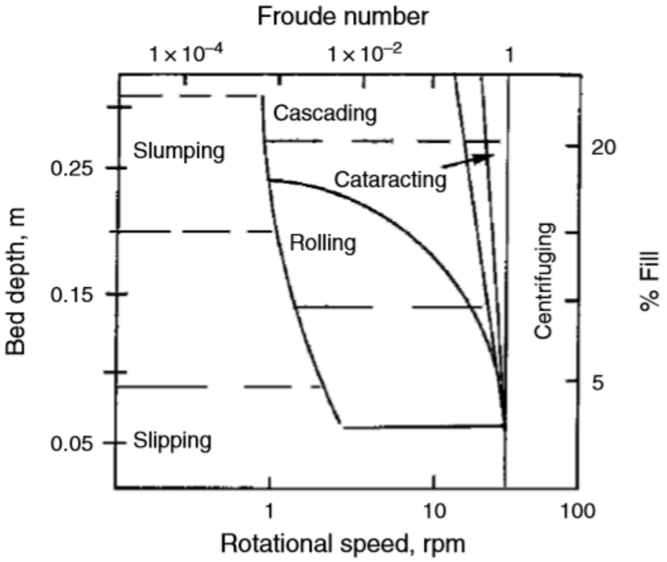


Figure 4; Froude number meaning diagrams resume. [3]

Derivate from the transversal movement of the feed bed, the concept of cascades is created which describes how many times the particle will “roll” or will be moved from the lower part of the feed bed to the top part. This movement happens on a tri-dimensional way as the particles advance on the kiln length, the result path of the particle would look like a distorted helicoidal shape.

In order to calculate the number of cascades per kiln revolution the author presents the following formula:

$$N_c = \frac{\pi}{\sin^{-1}\left(\frac{L_c}{2r}\right)} \tag{7}$$

Lc is the length of the chord and r is the distance of the tracked particle respected to the center of the kiln, r goes from 0 to the radius of the kiln.

It is also possible to estimate the axial movement of the particle per cascade, in other words - what distance the particle advances in the kiln per roll; the book presents the following way

$$z_o = \frac{L_c(\phi + \psi \cos \xi)}{\sin \xi} \tag{8}$$

where ψ is the bed angle relative to the axial plane.

The mean Axial transport velocity can be calculated as following:

$$u_{ax} = 2\pi rn\left(\frac{\phi + \psi \cos \xi}{\sin \theta}\right) \tag{9}$$

Finally, knowing the length and the mean axial velocity, it is possible to calculate the mean residence time as follows.

$$\tau = \frac{L \sin \xi}{2\pi r n(\phi + \psi \cos \xi)} \tag{10}$$

The book also proposes the following two simplifications of the formula in the case where the depth of the feed bed in the kiln is constant, there are no internal constructions inside the kiln and there is a low degree of filling, in minutes.

$$\tau = \frac{L\theta \sin \xi}{L_c \omega \tan \xi} \tag{11}$$

$$\tau = \frac{L \sin \xi}{2\pi r n \phi} \tag{12}$$

τ is the residence time in minutes, both equations allow us to calculate residence time but use a different set of variable.

2.3 Sai residence time

In the article “Residence Time Distribution and Material Flow Studies in a Rotary Kiln” written by P. S. T. Sai and other five authors, published in the year 1990 [11], the mean residence time relation with the height of a dam is explored via some experiments involving variables like feed rate of solids, slope and rotational speed of the kiln, type and size of the tracer, and dam height.

The experiments were run with coal inside, ilmenite and sand, with the respecting response angles of 27.4°, 21.8° and 24.6°. Other variables considered in the experiment are:

- Kiln Diameter – 147 mm
- Kiln Length – 5900 mm
- Dams heights: 15 and 28 mm
- Slope Degrees: 0.78, 1.1 and 1.37
- Rpm: 1, 2 and 3

After running 23 different combinations of the variables and measuring the mean residence time with tracer particles, they propose the following correlation, in minutes:

$$\tau = \frac{1315.2\, H^{0.24}}{\theta^{1.02} N^{0.88} F^{0.072}} \tag{13}$$

Where

τ Is the residence time in minutes

H Is the height of the dam in meters

θ Is the inclination of the kiln

N is the rpm

F is the Feed rate $\left({}^{kg}/_{hr}\right)$

And for the holdup, or in other words the amount of feed contained within the kiln at stabilized working conditions, in kilograms.

$$W = \frac{0.66F^{0.86}H^{0.4}}{\theta^{1.11}N^{0.9}} \qquad (14$$

2.4 Lui residence time

In the article "Mean Residence time and hold up of solid in rotary kiln" written by Xiao Yan Lui and Eckehard Specht, published in the year 2006 [7], The authors are faced with the same founding as this work and abundance of publications that are based on a handful of formulas, formulas that are described in this work as well, so they performed experiments with the aim to find the holdup of the feet inside the kiln and the mean residence time of the particles, for which they used a 400 mm diameter and 4600 mm length kiln, sand as feed, the kiln had discard dam of 25 mm and they changed the variables of feed rates and angular velocity.

The first equation mentioned for the residence time is a formula from paper called Passage of solid particles through rotary cylindrical kiln published in 1927 by J. D. Sullivan in the US bureau of miners Technical Paper [13]

$$\tau = 1.77\frac{L\sqrt{\theta}}{DN\beta} \qquad (15)$$

Where β is the inclination of the kiln on the horizontal axis.

From the performed experiments the resulting relation was proposed:

$$\tau = \frac{0.1026L^3}{\dot{V}}\left(\frac{\theta}{\beta}\right)^{1.054}\left(\frac{\dot{V}}{L^3N}\right)^{0.981}\left(\frac{L}{D}\right)^{1.1} \qquad (16)$$

Where the volumetric feed rate $\dot{V}$ is added using the units of ${}^{m^3}/_{min}$

Finally, a correlation that includes the height of a discharge dam is proposed

$$\tau = 1.77\frac{L\sqrt{\theta}}{DN\beta}e^{\left\{\left[\left(\frac{0.12L}{D}-3.86\right)\log\left(\frac{2.5\dot{V}}{NV}\right)+e^{2.3-\frac{0.32L}{D}}-1\right]\frac{H}{D-2H}\right\}} \tag{17}$$

τ is the residence time in minutes.

2.5 Bernard residence time

In the PhD. Thesis “Rotary Kiln Model” written by Pavel Bernard, published in the year 2015[2]. The author makes a compilation of the working parameters of a kiln, residence time, holdup, response angle, etc. there is an experiment performed and analyzed to validate and propose correlations.

The work has a relation to residence time very similar to the one of Boateng, but the calculation of the B factor is different.

$$\tau = \frac{0.23L}{sN^{0.9}D} \pm \frac{0.6BLG}{F} \tag{18}$$

$$B = 5d_p^{-0.5} \tag{19}$$

s is the slope $\left({}^{m}/_{m}\right)$

N is the revolutions per minute

G is the freeboard gas velocity $\left(\frac{kg}{hr\ m^2}\right)$

F is the feed $\left(\frac{k}{hr\ m^2}\right)$

B is a constant that depends on the material size

d_p is the particle diameter

It is also important to remark that the + symbol in the equation applies when the flow of air and feed is concurrent and – when the flow air and feed is countercurrent.

2.6 Perry residence time

On the Book “Perry´s Chemical Engineering Handbook” written by Robert H. Perry and Don W. Green, published in the year 1999[10]. The authors make a complete compilation of chemical engineering equipment, including: descriptions, history, chemical reactions, relation formulas, process diagrams and examples. In the chapter 23 page 60, the space velocity and residence time formulas are expressed.

For Space velocity

$$SV = 148 N \varphi D^3 \tan\theta \tag{20}$$

For Residence time

$$\tau = \frac{L}{60 \pi N D \tan\theta} \tag{21}$$

N is RPM

φ is the fraction of cross section occupied

D is the diameter in meters

L is the length in meters

τ is mean residence time in hours

SV is the Space velocity in $\left(\frac{ton}{m^3 day}\right)$

It also proposes a range for space velocities in different kind of industries

Process	Space Velocity
Cement, dry process	0.4-1.1
Cement, wet process	1.4-0.8
Cement, with heat exchange	0.6-1.8
Lime burning	0.5-0.9
Dolomite burning	0.4-0.6
Pyrite roasting	0.2-0.35
Clay calcination	0.5-0.8
Magnetic roasting	1.5-2.0
Ignition of inorganic pigments	0.15-2.0
Barium sulfide preparation	0.35-0.8

Figure 5; Proposes a range for space velocities. [10]

2.7 Comparison among proposed formulas

Based on all the source reviews it is possible to make a chart with all the available possibilities to calculate the mean residence time, with marking all the formulas which can be calculated without extracting data from the simulation or in other words with the available information for this work.

NUMBER	AUTHOR	FORMULA	POSSIBILITY OF CALCULATION
17	Bernard		Yes

		$\tau = \frac{0.23L}{sN^{0.9}D} \pm \frac{0.6BLG}{F}$ $B = 5d_p^{-0.5}$	
4	Boateng 1	$\tau = \frac{0.23L}{sN^{0.9}D} \pm \frac{BLG}{F}$ $B = sd_p^{-0.5}$	Yes
9	Boateng 2	$\tau = \frac{L \sin \xi}{2\pi rn(\phi + \psi \cos \xi)}$	/
10	Boateng 3	$\tau = \frac{L\theta \sin \xi}{L_c \omega \tan \xi}$	/
11	Boateng 4	$\tau = \frac{L \sin \xi}{2\pi rn\phi}$	/
15	Lui 1	$\tau = \frac{0.1026L^3}{\dot{V}} \left(\frac{\theta}{\beta}\right)^{1.054} \left(\frac{\dot{V}}{L^3 N}\right)^{0.981} \left(\frac{L}{D}\right)^{1.1}$	/
16	Lui 2	$\tau = 1.77 \frac{L\sqrt{\theta}}{DN\beta} e^{\left\{\left[\left(\frac{0.12L}{D} - 3.86\right) \log\left(\frac{2.5\dot{V}}{NV}\right) + e^{2.3 - \frac{0.32L}{D}} - 1\right] \frac{H}{D-2H}\right\}}$	
1	Peray 1	$\tau = \frac{11.4L}{NsD}$	Yes
2	Peray 2	$\tau = \frac{CL}{NsD}$ $C = 1.77\sqrt{\xi}$	/

20	Perry	$\tau = \frac{L}{60\pi ND \tan\phi}$	Yes
12	Sai	$\tau = \frac{1315.2\, H^{0.24}}{\theta^{1.02} N^{0.88} F^{0.072}}$	/
14	Sullivan	$\tau = 1.77 \frac{L\sqrt{\theta}}{DN\beta}$	/

Figure 6; Resident Time formulas

3. Literature Research - Rotary kiln.

Based on these sources it is possible to make the following conclusion about the rotary kiln general description, parameters, working principle and construction:

Historically the rotary kiln development and evolution have been closely related to the cement production, it is common to find publications that use the cement industry as a starting and reference point while making research, in other words all the narrative turns around Portland cement and how the acceleration of the world infrastructure construction depended on the ability to produce large amounts of high and predictable quality cement thus the rotary kiln evolution.

In order to fully understand what a rotary kiln is, it is important to notice what are the objectives of it, what kind of phenomena happens inside of it and what are the interaction in between them and all the other concepts and definitions derived from them.

Nowadays the rotary kiln is mainly used by the industry in many kinds of material processing, Lime Stone and cement production, as mentioned before, reduction of oxide ore as well as other metal processing steps, hazardous waste reclamation, cleaning of grounds by burning pollutants, ceramic aggregates production. But this equipment can be also applied in the food and pharmaceutical industry, or in any process that requires a continuous heat exchanger in between a gas and a solid phase.

A rotary kiln can be defined as a continuous heat exchanger between a gas and a solid phase, where the solid phase is transported and mixed by the spinning motion of the cylindrical body of the kiln and the heating source is provided by an open flame inside the kiln or by hot gases that are circulated inside of it.

As for any other equipment these defining attributes can be used to classify the rotary kilns, in the case of the internal shape those classifications are:

- Smooth
- Dams
- Hooks
- Mixers
- And the combination of the previous

For the case of how the heating source is provided the classification are:

- Open flame
- Hot gas

Finally, a third classification can be:

- Concurrent
- Countercurrent

3.1 Smooth Rotary kilns

A kiln can be named as smooth when its interior lacks any kind of internal construction leaving the shape of an empty cylinder on its insides, this is the most inefficient way to build it, but it's one of the most common because few materials can withstand the heat and periodic loads of the internal working of a kiln. As shown on the schematic Figure 1.

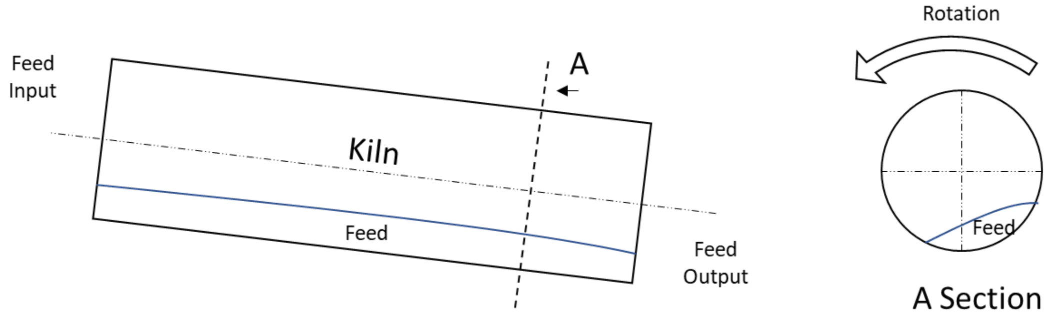


Figure 7; Rotary Kiln Smooth Walls.

3.2 Kiln with Dams

A Dam is used on a kiln to increase the residence time of the material by setting a constant level the material must reach in order to go for the next dam. A disadvantage of the damming system is that it doesn't distort the flow allowing the parts of the material to not be exposed to the hot gas. As shown on the schematic Figure 2.

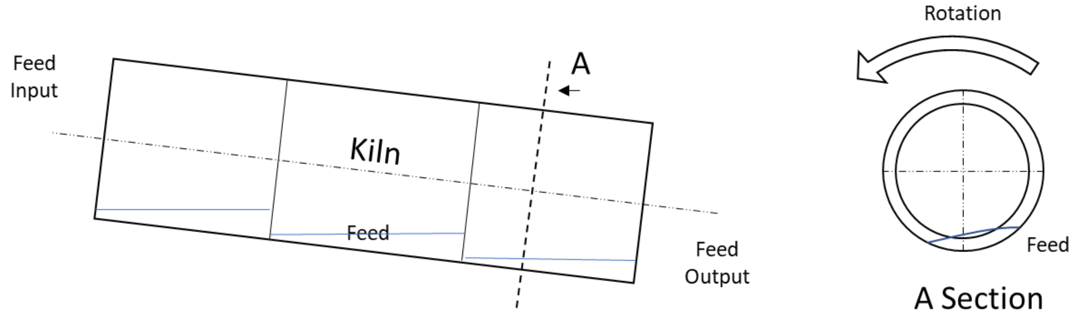


Figure 8; Rotary Kiln with dams.

3.3 Kilns with hooks

Hooks are added into the kiln in order to lift the material and dropping from the top of it, using the rotation of the kiln as a driving force for this movement. The hooks help to increment the heat transfer by convection by increasing the exposure time of the feed to the hot gases. As shown on the schematic Figure 3.

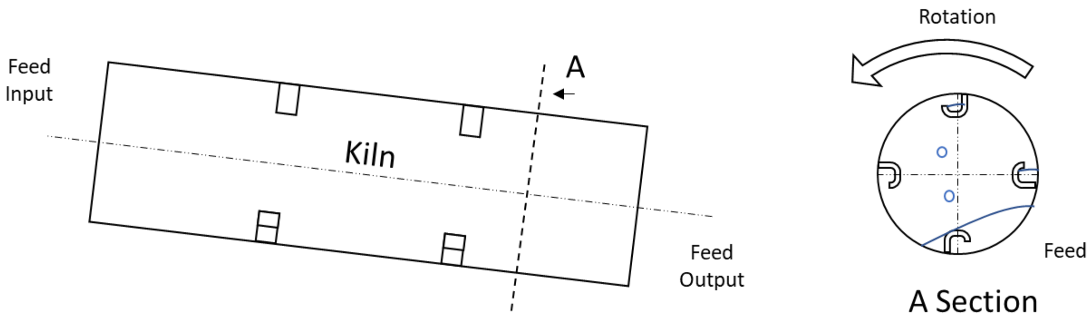


Figure 9; Rotary Kiln with hooks.

3.4 Kiln with mixers

These can be presented in a wide variety of shapes and positions along the kiln, its main function is to disrupt the flow of the feed in order to expose all the feed to the hot gases and therefore increase the efficiency of the kiln. As shown on the schematic Figure 4.

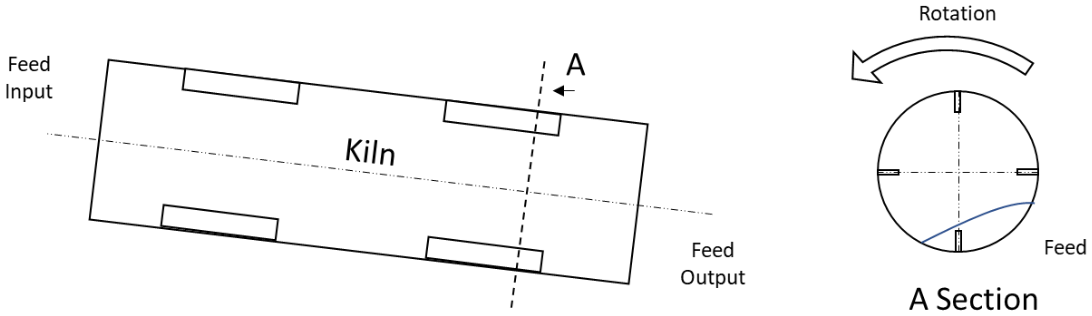


Figure 10; Rotary Kiln with mixers.

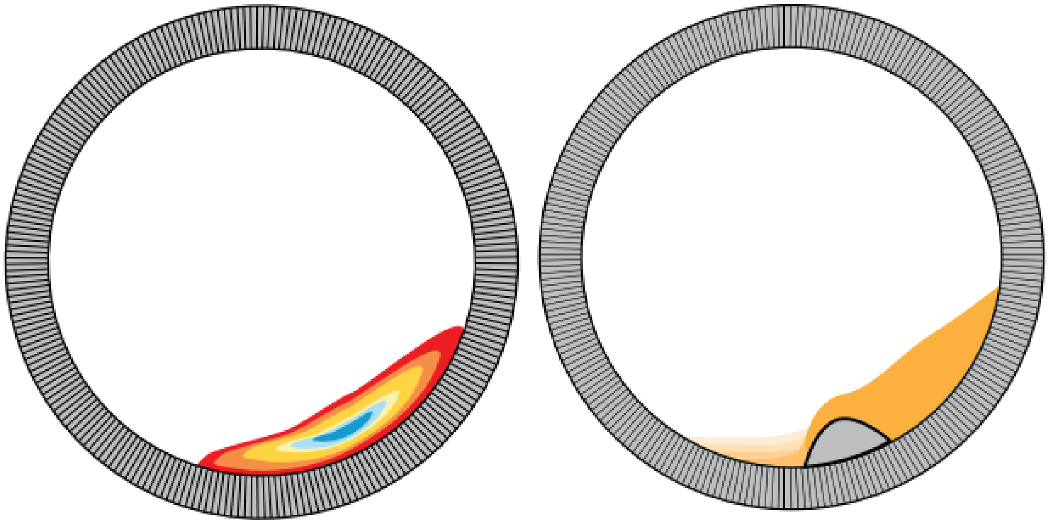


Figure 11; Rotary Kiln mixers result [5].

As it is shown on the previous schematics Figure 5 from the sales pamphlet from FEECO [5] the mixers inside the kiln eliminate the temperature layering inside the feed bed.

3.5 Open flame

The open flame heating system consists of a burner located inside of the kiln most commonly at the end, where the feed exits. This kind of heat source brings the benefit of having and additional heat transfer mechanism, the radiation of the flame to the feed and the surrounding walls as well as the convection from the flue gasses as they travel along the body of the kiln. As shown on the schematic Figure 6.

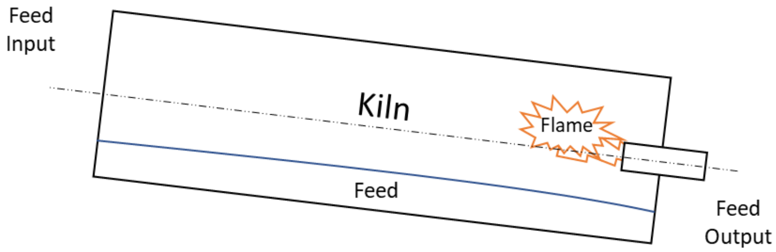


Figure 12; Open Flame Burner.

3.6 Hot Gas kilns

This kind of kiln lack an open flame inside of them and instead of it they use the flow of hot gas to provide the heat for the system, the hot gas is usually the flue gas of a previous process. This kind of kiln is usually used as a preheating or recovering unit, but it can be used as well for temperature sensible materials. As shown on the schematic Figure 7.

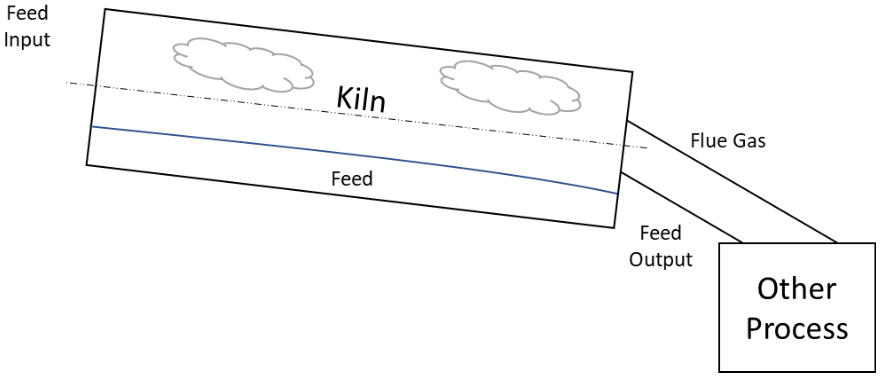


Figure 13; Heated Gas Kiln.

3.7 Kiln construction

These kinds of equipment are massive, weighing several tones, and if we add the feed material inside of them, the construction of them has to be very resilient and to add another restriction to the design of this kind of machines, the kiln has to be able to rotate along its axis and have fixed input and output points for the feed and gases.

Many companies that build them have reached similar ways to solve this problem, generally reinforcing the cylindrical body of the kiln on the support points as well as a holding wall on the edge of the cylinder to avoid the sliding of the kiln due to its inclination.

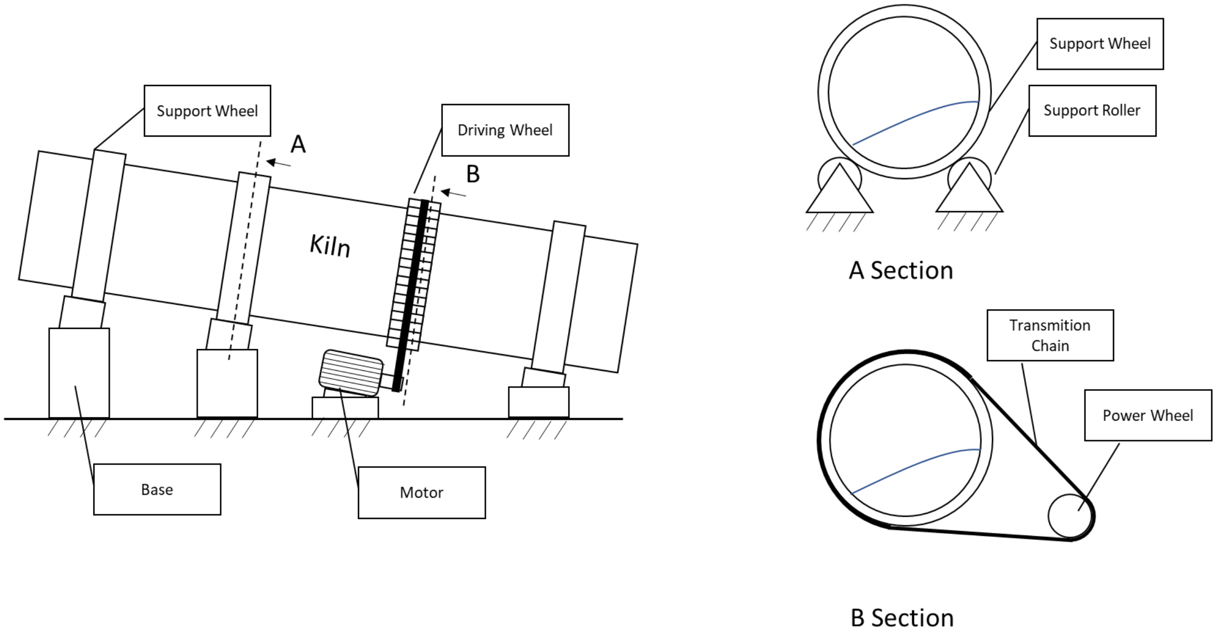


Figure 14; Driving gear, Rotary Kiln.

As shown on the previous figure 8 there are two kinds of ring reinforcements added to the cylindrical body, one works as support point in contact with rollers that allows the kiln to spin while holding its weight, the other kind of added ring usually has teeth or grooves that work with a transition band, chain or directly with a gear and provide the energy for the spinning.

3.7.1 Kiln isolation

The inside of a kiln can reach temperatures up to 1500°C [5] depending on what kind of burner and fuel is used to generate it. This means that the building materials of it will be submitted not only to the stress of holding its weight and the one of the feeds, the rotation along the axis, but also to the weakening effect of the high temperature.

For this reason and also to increase the efficiency of the kiln by reducing the heat loses, an isolation layer is added. There are two main ways to add this inside a layer - castable and bricks:

Castable: this technique uses paste like materials like concrete to coat the inside of the kiln, different layers of different materials and thickness can be added on a concentrically fashion, anchoring points are needed to hold the layers.

Bricks: premade bricks are built inside the kind to create the isolation and refractory layers, anchoring points and bounding materials for the bricks are optimal according to the specific needs of the process.

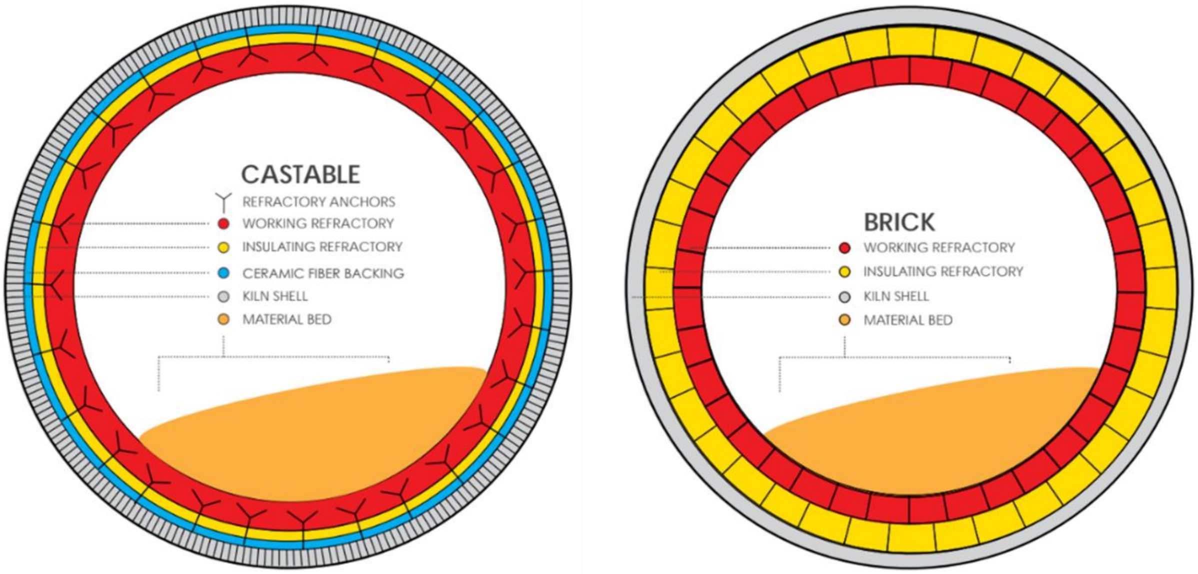


Figure 15; Rotary Kiln internal isolation [5] .

The previous figure 9, is an example of the two different kinds of isolating techniques.

4. Literature Research - Heat transfer

Similarly, as in most of all-natural phenomena all the three heat transfer phenomena are present inside of a rotary kiln, but not all of them have the same impact on the total amount of transferred heat. In order to simplify the model some of them can be ignored which depends on what are the characteristics of the kiln and what exactly is being studied, for example, on a hot gas kiln with flue gas temperatures between 100 – 300 °C the radiation phenomena could be omitted.

Other example of this could be the heat transfer in between the particles of the feed. If kiln has some kind of mixers or hooks, it is possible to assume that the temperature of the feed bed is constant due to the constant disruption of the feed flow. Unlike the case where the kiln has a smooth interior, which is dependent on the properties of the material, it is possible that it develops different zones and death spots where particles are trapped and effectively creating different temperatures in within the feed bed.

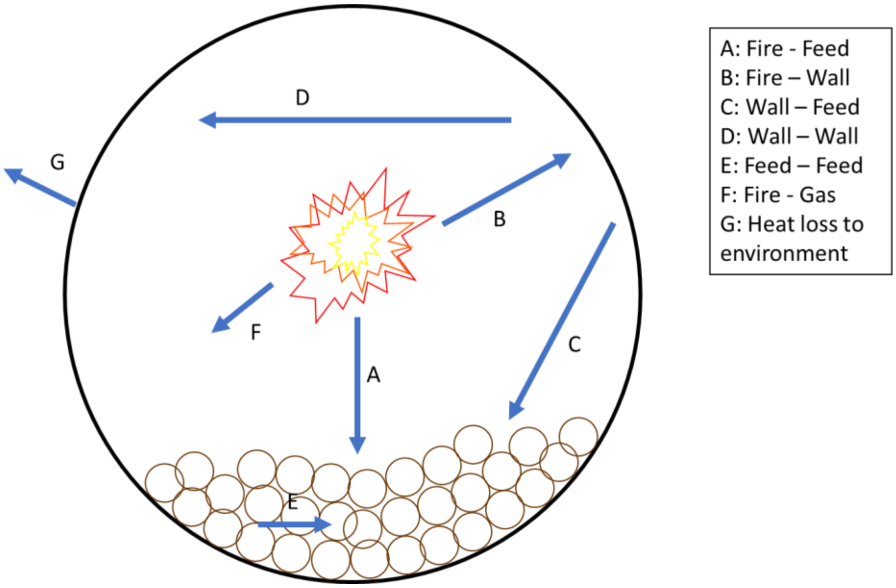


Figure 16; Rotary Kiln Heat Transfer Media. [3]

The previous figure represents all the possible combinations in between bodies for the heat exchange, it is possible that; convection, conduction and radiation happen in between each other, but as previously mentioned, some of them are too weak or can be omitted depending on the working conditions and parameters of the kiln. Usually Convection in between the surface of the feed bed is the dominant heat transfer media, but when the bed feed is close to an open flame source the radiation in between the flame and the feed gains importance.

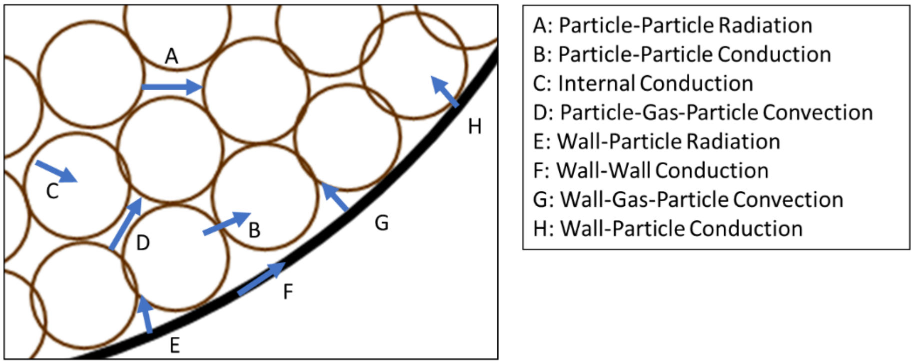


Figure 17; Rotary Kiln Heat Transfer Media, in the Bed.[3]

The heat transfer phenomena in within the feed bed requires special attention due to its complexity, as a result of the granular nature of the feed little spaces filled with gas are created, allowing radiation and convection phenomena to happen.

Other heat transfer phenomena worth mentioning is the conduction between the wall and the feed bed, due to the rotation of wall at some moment the wall would be exposed to the radiation and convection of the fire and flue gases but after half revolution the same spot of the wall would be transferring the heat to the feed. In other words, due to the nature of the phenomena the same spot would be receiving heat and transferring heat in a different moment.

It is possible to divide the kiln into three main sections, based on the temperature of the feed. This division can also be done on the water content of feed. The length or existence of each sections depends on the working conditions of the kiln for example:

- Initial temperature and humidity of the feed
- Kiln dimensions
- Source, location and intensity of the heat
- Internal construction of the kiln; dams, mixers, hooks

The tree sections according to the water content and temperature of the feed are:

1. Heating
2. Drying
3. Burning

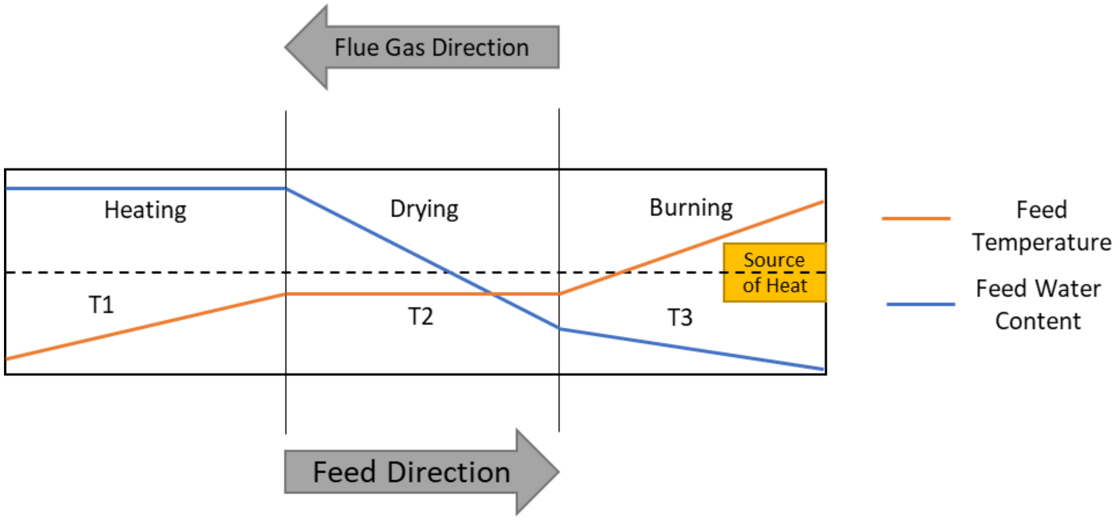


Figure 18; Temperature and Water content Profile of the Feed.

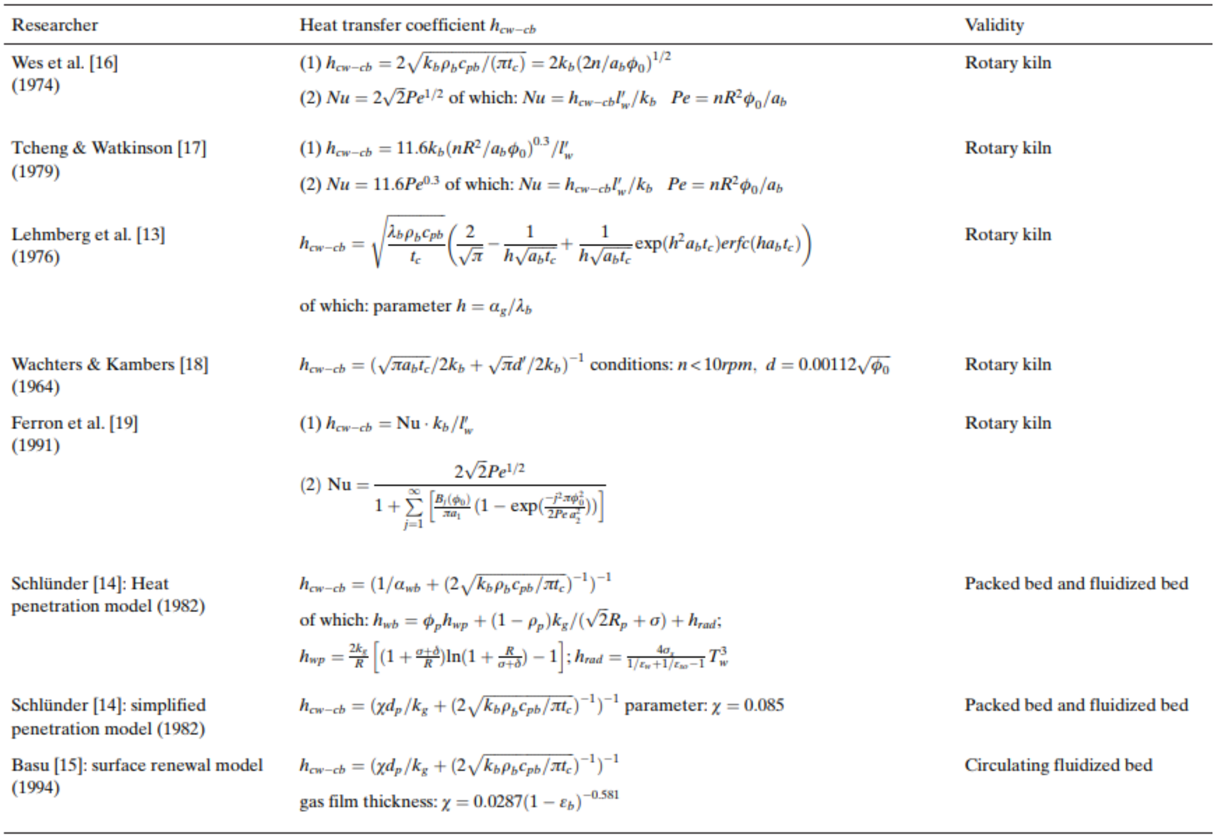
Heating: this happens on the intake of the feed, when the rotary kiln is on a countercurrent configuration, the coldest flue gas is in contact with the coldest feed, also the gases carry the water from drying section so not much water is striped from the feed. The main function of this section as its name indicated is to increase the temperature of the feed until evaporation point. The temperature of the feed in this section goes from ambient temperature or the initial temperature of the feed to 100°C. A way to reduce the size of this section and to optimize the kiln is to increase the input temperature of the feed.

Drying: here the evaporation of the free water happens, and therefore the temperature remains constant around 100°C, it is the mid sections of the kiln. A common way to optimize this section is with the use of hooks that lift the feed and drop it from the highest point and thus not only increase the contact time of the feed with the hot gas but to increase the relative velocity of the feed vs the hot gases, thus increasing the convection and evaporation of the gases as well.

Burning: here the bounded water is evaporated, chemical reactions usually happen in this section, the temperature of the feed goes from 100°C till the final temperature usually between 600°C to 800 °C, but it can be more than 1000°C depending on the application and process. Here it’s very difficult to use some kind of internal construction because of the high temperatures. Few materials are able to withstand them while keeping its strength and resistance. A way to optimize it, is with the use of isolation on the kiln to reduce the heat loss, as well as using the most efficient way to produce the necessary heat. It is important to mention than on this section the heat transfer by radiation represents 90% of the total, followed by convection with 9% and finally conduction with the remaining 1% [3]

4.1 Heat Transfer Between Covered Wall and Bed

As it was mentioned before, the heat transfer between the material bed and the heated rotative wall presents a special challenge due to the transient nature of it. There have been many attempts to create a model to describe this phenomenon. For instance, the following one:



Researcher	Heat transfer coefficient h_{cw-cb}	Validity
Wes et al. [16] (1974)	(1) $h_{cw-cb} = 2\sqrt{k_b \rho_b c_{pb}/(\pi t_c)} = 2k_b(2n/a_b\phi_0)^{1/2}$ (2) $Nu = 2\sqrt{2}Pe^{1/2}$ of which: $Nu = h_{cw-cb}l'_w/k_b \quad Pe = nR^2\phi_0/a_b$	Rotary kiln
Tcheng & Watkinson [17] (1979)	(1) $h_{cw-cb} = 11.6k_b(nR^2/a_b\phi_0)^{0.3}/l'_w$ (2) $Nu = 11.6Pe^{0.3}$ of which: $Nu = h_{cw-cb}l'_w/k_b \quad Pe = nR^2\phi_0/a_b$	Rotary kiln
Lehmberg et al. [13] (1976)	$h_{cw-cb} = \sqrt{\frac{\lambda_b \rho_b c_{pb}}{t_c}}\left(\frac{2}{\sqrt{\pi}} - \frac{1}{h\sqrt{a_b t_c}} + \frac{1}{h\sqrt{a_b t_c}}\exp(h^2 a_b t_c)erfc(h a_b t_c)\right)$ of which: parameter $h = \alpha_g/\lambda_b$	Rotary kiln
Wachters & Kambers [18] (1964)	$h_{cw-cb} = (\sqrt{\pi a_b t_c}/2k_b + \sqrt{\pi}d'/2k_b)^{-1}$ conditions: $n < 10rpm, \ d = 0.00112\sqrt{\phi_0}$	Rotary kiln
Ferron et al. [19] (1991)	(1) $h_{cw-cb} = \mathrm{Nu} \cdot k_b/l'_w$ (2) $\mathrm{Nu} = \frac{2\sqrt{2}Pe^{1/2}}{1+\sum_{j=1}^{\infty}\left[\frac{B_j(\phi_0)}{\pi a_1}(1-\exp(\frac{-j^2\pi\phi_0^2}{2Pe\,a_2^2}))\right]}$	Rotary kiln
Schlünder [14]: Heat penetration model (1982)	$h_{cw-cb} = (1/\alpha_{wb} + (2\sqrt{k_b\rho_b c_{pb}/\pi t_c})^{-1})^{-1}$ of which: $h_{wb} = \phi_p h_{wp} + (1-\rho_p)k_g/(\sqrt{2}R_p + \sigma) + h_{rad}$; $h_{wp} = \frac{2k_g}{R}\left[(1+\frac{\sigma+\delta}{R})\ln(1+\frac{R}{\sigma+\delta}) - 1\right]; h_{rad} = \frac{4\sigma_s}{1/\varepsilon_w + 1/\varepsilon_{so} - 1}T_w^3$	Packed bed and fluidized bed
Schlünder [14]: simplified penetration model (1982)	$h_{cw-cb} = (\chi d_p/k_g + (2\sqrt{k_b\rho_b c_{pb}/\pi t_c})^{-1})^{-1}$ parameter: $\chi = 0.085$	Packed bed and fluidized bed
Basu [15]: surface renewal model (1994)	$h_{cw-cb} = (\chi d_p/k_g + (2\sqrt{k_b\rho_b c_{pb}/\pi t_c})^{-1})^{-1}$ gas film thickness: $\chi = 0.0287(1-\varepsilon_b)^{-0.581}$	Circulating fluidized bed

Figure 19; Heated wall to Feed Bed Conduction Formulas [6]

4.2 The convective Heat Transfer Coefficient

A Proposed equation for the convective heat transfer in-between the freeboard gas - exposed wall and the free boar gas and exposed bed surface are[6]:

$$Nu_{g-ew} = h^c_{g-ew} D_e/k_g = 1.54\ \mathrm{Re}_g^{0.575}\ \mathrm{Re}_w^{-0.292} \qquad (22)$$

$$Nu_{g-eb} = h_{g-eb} D_e/k_g = 0.46\ \mathrm{Re}_g^{0.535}\ \mathrm{Re}_w^{0.104}\eta^{-0.341} \qquad (23)$$

These equations were obtained through correlation method. The complementary equations are:

$$Re_g = V_g\frac{D_e}{v} \quad 1600 < Re_g < 7800 \qquad (24)$$

$$Re_w = {D_e}^2\frac{w}{v} \quad 20 < Re_w < 800 \qquad (25)$$

$$\eta = \frac{(\phi_0 - \sin\phi_0)}{2\pi} \tag{26}$$

$$D_e = 0.5D\frac{(2\pi - \phi_0 + \sin\phi_0)}{\left(\pi - {\phi_0}^2 + \sin{\phi_0}^2\right)} \tag{27}$$

where the valid parameters for the Reynolds number for the freeboard gas and the inside wall are shown on the equations 4 and 5 respectively, η is the packing ratio of solid, which is calculated using the half central angle of sectional solid bed, in radians. D_e is the equivalent diameter of the freeboard region.

4.3 The Radiant Heat Transfer

The radiant heat transfer from the hot gas to the bed surface can be described by[6]:

$$h^r_{g-eb} = \frac{Q^r_{g-b}}{A_b\left(T_g - T_b\right)} = \frac{(E_g - J_b)/R_{g-b}}{A_b\left(T_g - T_b\right)} \tag{28}$$

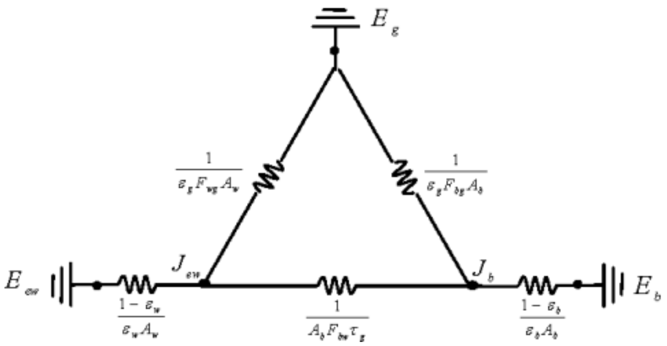


Figure 19; Schematic description of the radiant heat transfer inside the kiln [6].

The radiant heat transfer from the hot gas to the wall surface can be described by:

$$h^r_{g-ew} = \frac{\sum Q^r_{g-wi}}{A_w\left(T_g - T_w\right)} = \frac{\sum (E_g - J_{wi})/R_{g-wi}}{A_w\left(T_g - T_w\right)} \tag{29}$$

The radiant heat transfer from the wall surface to the bed surface can be described by:

$$h^r_{ew-eb} = \frac{\sum Q^r_{wi-b}}{A_b(T_w - T_b)} = \frac{\sum (J_{wi} - J_b)/R_{b-wi}}{A_b(T_w - T_b)} \tag{30}$$

The view factors are:

$$F_{bg} = F_{wg} = F_{bw} = 1 \tag{31}$$

4.4 Heat loss to the Environment

The convective heat transfer loss from the outer shell of the kiln and the environment is[6]:

$$\text{when: } \left(\frac{\mathrm{Re}_w}{\sqrt{Gr}} \geq 0.2\right), \tag{32}$$

$$h^c_{sh-a} = \frac{0.11 k_a \, \mathrm{Pr}^{0.36}}{D}\left(0.5\mathrm{Re}_w^2 + \mathrm{Re}_a^2 + Gr\right)^{0.35} \tag{32}$$

$$\text{when: } \left(\frac{\mathrm{Re}_w}{\sqrt{Gr}} < 0.2\right), \quad h^c_{sh-a} = \frac{k_a \, \mathrm{Pr}^{0.3}}{D} C\mathrm{Re}_a^N \tag{34}$$

5 Literature Research - material

Clay is the raw material that the rotary kiln as described in this work uses as. From raw clay, to a commercial product, it is necessary to investigate what the clay and its properties are and what process is necessary to obtain the desired final product.

On the Book “Ceramics are more than clay alone: raw materials, products, applications” written by Boremans, published in the year 2003[4]. The authors make a complete compilation of what is clay and ceramics, its components, chemical reaction involved on its process, formation processes, and properties and processing of them. Based on it, it is possible to conclude the following about clay and ceramics

5.1 Clays - Earth

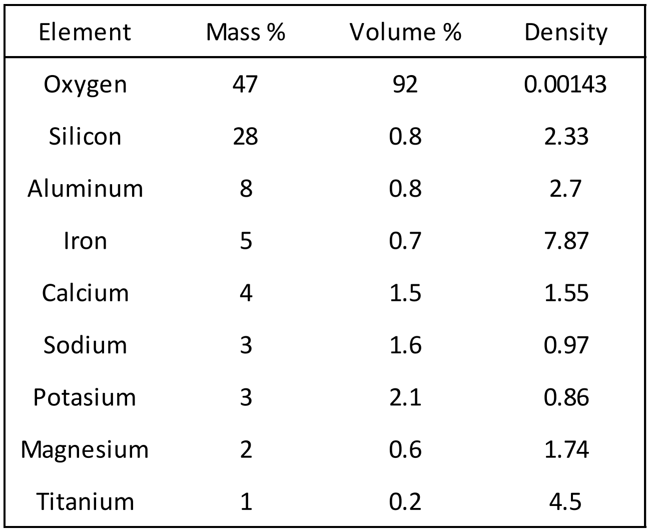
All human activities including the ones related to mineral extraction occur on the lithosphere, from the Greek “lithos” stone, it has an average depth of 35 kilometers where its thinnest part is around 20 and the thickest circa 60 kilometers [4]. Although it is considered as a solid, on larger time lap natural forces like erosion and tectonic forces will have a great impact, moving materials from a place to place but not only on superficial level but also transporting it from the earth inner layers to the surface and vice versa. This natural process of transformation enriches the pool of available minerals, making the access to sedimentation and metamorphic minerals possible.

Minerals in the form of rocks can be classified in three main groups:

- Igneous or magmatic: these rocks are formed from the cooling of lava and they have no organic materials on them, they have the same composition as the earths mantel.
- Sedimentary: these rocks are formed from sedimentation process such as water or wind erosion, the deposits on this kind of materials. This process tends to generate relatively pure deposits because particles with same density, shape and size will tend to accumulate in the same zones. It can contain organic materials.
- Metamorphic: these rocks are formed inside the lithosphere where temperature, pressure, exposure to the water and its pH will trigger chemical reactions that will change the composition of the rocks.

The composition of the earth crust is relatively well known as well as its conditions, the thickness of each layer is not constant, in other words it varies from region to region.

The earth compositions is:



Element	Mass %	Volume %	Density
Oxygen	47	92	0.00143
Silicon	28	0.8	2.33
Aluminum	8	0.8	2.7
Iron	5	0.7	7.87
Calcium	4	1.5	1.55
Sodium	3	1.6	0.97
Potasium	3	2.1	0.86
Magnesium	2	0.6	1.74
Titanium	1	0.2	4.5

Figure 21; Earth composition [4].

These elements are rarely found on a pure way, most of the time they are found in oxide minerals: $SiO_2, Al_2O_3, CaO, MgO, Na_2O, FeO, K_2O, TiO_2, P_2O_5$

5.2 What is Clay?

Clay can be defined as “a term that refers to a material present in nature which mainly consists of fine granular minerals, which generally exhibit plastic behavior at certain water contests and which harden after drying and baking. Although clay usually consists of phyllosilicates, it can also contain other materials which do not affect its plastic and hardening behavior. These so-called associated phases can contain minerals like quartz, calcite, dolomite, feldspars, oxides, hydroxides, organic materials and non-crystalline phases.” 14].

It can also be said that clay is formed by a sedimentation and igneous process, where its components are deposit in its recipient by natural forces, such as water drag, soil erosion and movements of the earth's crust, for later be chemically transformed by pressure, thermal or chemical process into clay, this mineral metamorphosis usually occur in the presence of high temperatures, due to the depth of the deposit, geological activity of the area or frictional forces due to the earth pressure, as well as water in a wide range of pH values, acidic or alkaline solutions. Thus, the composition, properties and characteristics of clay can vary in wide range, making the definition of clay and therefore ceramics not the one of an individual material but of the one of a group of materials[4].

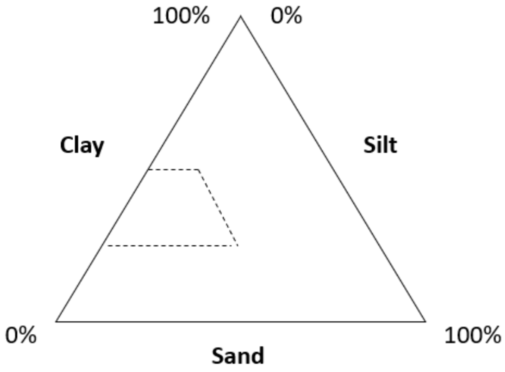


Figure 22; Clay normal composition parameters [4].

Clay is usually not found on high purities, although it is possible, it is found on a mixture with sand and silt. Where the average clay deposit would have the following composition: 30% clay, 30% silt and 40% sand.

Clay can be classified on its sand content:

- Heavy clay: less than 40% by weight of sand.
- Light clay: between 40% and 60% by weight of sand.

5.3 Clay formation

Clay is the result of the erosion of igneous and sedimentary rocks, depending on factors like climate, vegetation, texture of rocks, topography and composition of the ground. This erosion is made via weathering process that can be subdivided into chemical and mechanical process.

- **Chemical erosion**: is a complex process where concentration gradients of the minerals play a role. It is also worth mentioning that water or a liquid solution is necessary for this process to happen. Conditions as solution acidity or alkalinity and crystalline structures of the minerals play a role on the speed and overall transformation of the ground [4].

  A general view of the chemical erosion can be described as:

$$\textbf{Primary Minerals} + \textbf{Supplied Solution} \rightarrow \textbf{Secondary Minerals} + \textbf{Drained Solution}$$

Figure 9; Chemical erosion over view [4].

There are four kinds of classification of chemical erosion according the solutions present:

1. Acidolysis: Its chemical erosion under the presence of water and acid, pH < 7
2. Alkalinolysis: Its chemical erosion under the presence of water and acid. pH >7
3. Hydrolysis: Its chemical erosion under the presence of water. pH = 7
4. Salinolysis: Its chemical erosion under the presence of saline solution, of any kind of salt. pH ≈ 7

- **Mechanical erosion**: is the process that results from the accumulation of stresses generated by:

   1. **Thermal erosion:** a cyclic difference in temperature in the zones of the mineral deposit, and therefore thermal expansion. For example, day and night and winter and summer. This cycle of expansion and shrinking of the material plus the weight and lack of space to displace itself, results in cracks in the rocks, if water is added to the system, it will fill the gaps in between the rock particles and if it froze expand, creating more and bigger gaps, that will be again fill with water and on the cold part of the cycle froze again, creating a "gridding" effect.
   2. **Wind/water erosion:** is generated by the friction in between the solid phase and fluid phase, a denser fluid like water will have a faster more noticeable effect than wind, the friction in between them can also be increase by solid particles carry out by the fluid, such as dust, sand or small rocks.
   3. **Vegetation erosion:** is generated by the roots forcing themselves in the ground and weight of the vegetation in the area.
   4. **Glacier erosion:** is generated by the friction of an ice sheet slowly but steadily moving over the surface of a valley.

An example of the formation of a clay mineral, kaolinite, from an igneous rock orthoclase.

$$\underbrace{2\,K[AlSi_3O_8]}_{\boxed{\text{Orthoclase}}} + \underbrace{3\,H_2O}_{\boxed{\text{Water}}} \rightarrow \underbrace{Al_2Si_2O_5(OH)_4}_{\boxed{\text{Kaolinite}}} + \underbrace{4\,SiO_2}_{\boxed{\text{Quartz}}} + \underbrace{2\,K^+ + 2\,OH^-}_{\boxed{\text{Potassium hydroxide in solution}}}$$

Figure 23; Formation of Kaolinite, chemical erosion [4].

The formation of the kaolinite required abundant water and a relative quick drainage of the Potassium hydroxide in solution. If these conditions are not achieved another clay mineral Illite is formed instead.

$$\underbrace{3\,K[AlSi_3O_8]}_{\boxed{\text{Orthoclase}}} + \underbrace{2\,H_2O}_{\boxed{\text{Water}}} \rightarrow \underbrace{KAl_2(Al\,Si_3)O_{10}(OH)_2}_{\boxed{\text{Illite}}} + \underbrace{6\,SiO_2}_{\boxed{\text{Quartz}}} + \underbrace{2\,K^+ + 2\,OH^-}_{\boxed{\text{Potassium hydroxide in solution}}}$$

Figure 24; Formation of Illite, chemical erosion [4].

If the conditions for erosions keep constant the Orthoclase will be further decomposed into Gibbsite $Al[OH]_3$ and Boehmite $AlOOH$, both components of the aluminum ore Bauxite.

5.3.1 Clay Composition

The clay composition, as previously mentioned varies in between clay fields but it can be said the general elements are:

Material	Percentage by Weight
• Organic Material	0.5 – 2.5
• Clay Minerals (silicate minerals)	15 – 100
• Quartz, Tridymite and Cristobalite	40 – 70
• Feldspars, Amphiboles and other non-clay Silicates	1 – 9
• Water	
• Other compounds	

Figure 25; Clay Composition [4].

The other compounds that could or could not have an impact on the properties of the clay and ceramic are:

- Salts
    - Sodium sulfate Na_2SO_4
    - Sodium chloride $NaCl$
    - Magnesite $MgCO_3$
    - Magnesium sulfate $MgSO_4$
    - Dolomite $MgCa(CO_2)_3$
    - Calcium sulfate $CaSO_4$
    - Calcium carbonate $CaCO_3$
    - Iron Sulfide FeS
    - Pyrite FeS_2
    - iron sulfite $FeSO_3$
    - iron carbonate $FeCO_4$
    - Baryte $BaSO_4$

- Oxides
    - Rutile TiO_2

Anatase	TiO_2
Brookite	TiO_2

- Aluminum oxide and hydroxide

Gibbsite	$Al[OH]_3$
Boehmite	$AlOOH$

- Iron oxides and hydroxides

Hematite	Fe_2O_3
Goethite	$Fe_2O_3H_2O$
Magnetite	Fe_3O_4
Maghemite	Fe_2O_3
Lepidocrocite	$FeOOH$
Hercynite	$FeOAl_2O_3$

5.4 Types of clay

There are many ways to classify clay, according to its color, particle size, composition, formation period, location. Some of the possible tags are:

- Primary Kaolin or China Clay: it’s very pure and has white color, it lies in the same place where it was formed and therefore it has not been bared to erosion. It has relatively big particles and is mainly used for porcelain production.
- Secondary Kaolin: it has already been transported by a natural process; its particle size is smaller and therefore more plastic. It has a yellowish color.
- Ball Clay: it has been transported into a deposit by water, has higher contents of carbonates, extremely plastic, it has a grey or brown color.
- Fire Clay: it has been transported in the deposit by erosion and wind. Has a high concentration of metal oxides and quartz, it has a variety of colors.
- Stoneware clay: it’s a mixture in between ball and fire clay, and its properties are in between them as well, it’s quite rare.

5.5 Clay Properties

As it was mention for the clay classification, and due to its wide range of components, each clay mine is almost unique. The study of the properties of the clay minerals mixture helps us to determine its usage and quality. Some of the most frequently study properties are [4]:

- Adsorption and specific area
- Chemical composition
- Color before and after baking
- Crystalline structure
- Drying behavior
- Firing behavior
- Grain size distribution

- Mineralogy
- Plasticity
- Rheology
- Texture
- Water absorption

Color before and after baking: depends on the Ca/Fe ratio, as well as other pollutants in the mix.

Drying behavior: clays with smaller particle size tend to develop cracks on its surface when drying, to avoid this, it is necessary to add sand to the mixture to increase its porosity or to reduce the intensity of the drying making it a longer process.

Firing behavior: due to its contend of organic material, water and other volatile substances, the firing process has to be gentle, to avoid cracking or small explosions of the clay.

Plasticity: according to the book [4] Ceramics are more than clay alone: raw materials, products, applications, clay plasticity is “the property of a substance to react to the influence of an external force with a lasting change in shape but without exhibiting cracks” [4].

An example of clay properties and in composition can be:

	Sample 1	Sample 2	Sample 3
Chemical Analysis after Calcination [%]			
SiO_2	58.70	74.64	90.63
Al_2O_3	33.00	17.55	7.30
TiO_2	1.48	1.35	0.81
Fe_2O_3	1.78	4.25	0.40
CaO	0.47	0.18	0.12
MgO	0.66	0.30	0.1
Na_2O	0.28	0.08	0.00
K_2O	3.66	1.60	0.32
Mass loss in ignition [%]	10.12	5.30	2.96
Whole Carbon [%]	2.50	0.05	0.00
Fired Color 1200 °C	Light Cream	Light Red	White
Particle Size Distribution [%]			
$> 200\ \mu$	1.30	1.80	4.00
$> 63\ \mu$	2.50	6.10	27.75
$< 1\ \mu$	70.00	49.00	14.00
Firing Shrinkage [%]			
1050 °C	7.70	1.87	0.00
1200 °C	11.30	5.01	0.96
Water absorption [%]			
1050 °C	7.80	13.98	15.00
1200 °C	0.20	6.35	12.00
Dry bending strength $\left[\frac{N}{mm^2}\right]$	7.50	3.42	1.60

Figure 26; Clay properties samples [4].

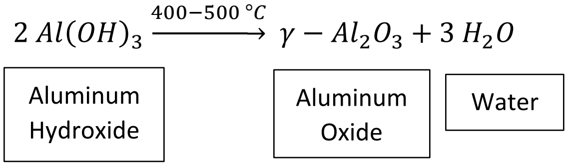
5.6 Ceramics

5.7 Synthetic Ceramics

Synthetic ceramics are also known as non-clay ceramics, these kinds of materials are used for two primary reasons:

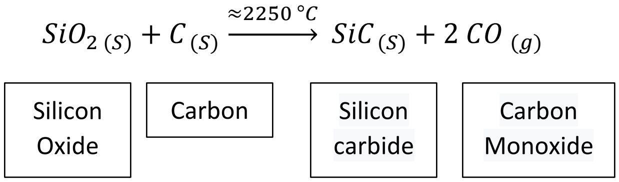
1. The required material components do not occur in nature.
2. The required properties of the material do not occur in nature for example: purity and grain size.

An example of synthesis of a ceramic material are the following



$$2\ Al(OH)_3 \xrightarrow{400-500\ °C} \gamma - Al_2O_3 + 3\ H_2O$$

Figure 27; Formation of Aluminum Oxide, Synthetic Ceramic [4].



$$SiO_{2\ (S)} + C_{\ (S)} \xrightarrow{\approx 2250\ °C} SiC_{\ (S)} + 2\ CO_{\ (g)}$$

Figure 28; Formation of Silicon Carbide, Synthetic Ceramic [4].

5.8 Ceramic Heat Treatment

There are three stages of heat treatment for ceramics and they develop on the following order:

1. Drying, removing of free water.
2. Firing, removing of bounded water.
3. Sintering, densifying of the ceramic by baking.

Drying

For the drying process three main condition must be fulfilled - a relatively high temperature, speed of the flow and low humidity of the air. A phenomenon known as drying shrinkage occurs at the heat treatment process because as the water leaves the pores of the clay/ceramic the particles are able to move closer together.

The drying process can be plotted as follows.

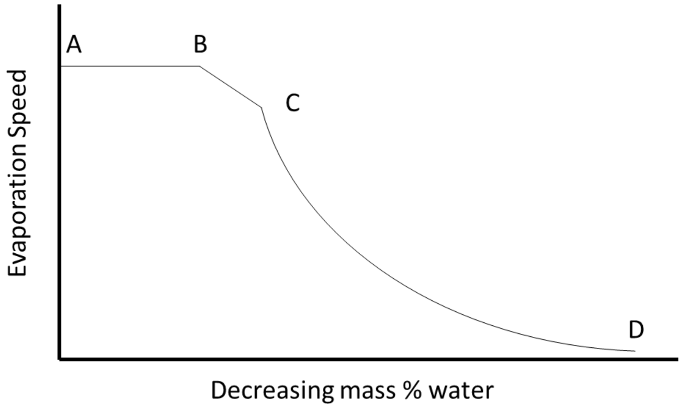


Figure 29; Drying Process, Heat treatment.[]

- From A to B the evaporation occurs on the pores of the surface exposed to the drying media.
- The evaporation of the water from point B to C is reduced as some of the pores of the clay get dry.
- The speed of evaporation speed from C to B is governed by the water diffusion inside the clay, moving from the inside of the body to the surface.

Some of the problems that can be found on the drying process of clay are the appearance of cracks and fractures on the clay surface due to a fast and unequal drying of it, as well as dissolved salts transported by the water to the surface of the body.

6.2.1 Firing

At these stage non-wanted components like binding elements and flocculants are decomposed in a pyrolysis effect, burned and eventually evaporated. The temperatures for decomposing are in a range between 200 and 400 °C and for burning and evaporating the range goes in between 400 and 600 °C.

If the firing increase of temperature happens too fast, the gases produced from the combustion and evaporation of the binding elements could generate cracks, or under specific circumstances even explosions.

6.2.2 Sintering

After the firing, the temperatures keep rising to a range in between 1200 and 1600 °C for the phenomena called sintering happen, where the pores left by the evaporated water, binding elements and flocculants are dissolve leaving a denser body with greater cohesion.

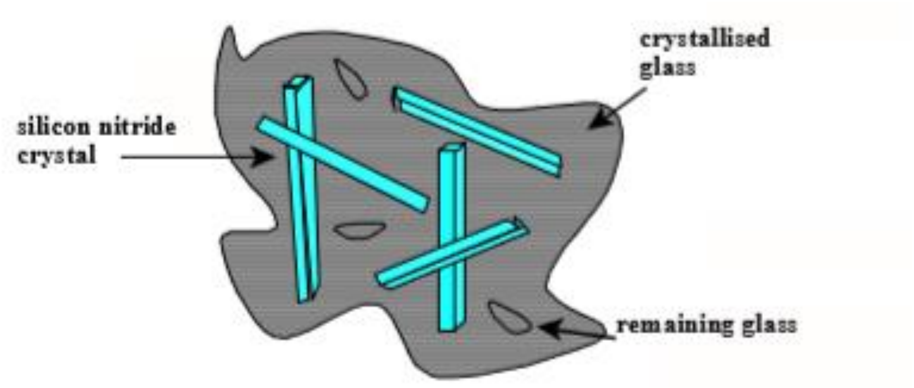


Figure 30; Result after Cooling, Sintering. [4].

$$3\ Si_{(S)} + 2\ N_{2\ (g)} \rightarrow Si_3N_{4\ (S)}$$

Silicon Nitrogen Silicon Nitride

Figure 31; Clay sintering reaction, example. [4].

For more information refer to Annex 1

5.9 Expanded Clay

From the previous chapter, it is possible to conclude that the heating of the clay has to be fast, but not so much since that would cause the clay/ceramic explosion. The book mentions that if the increase of temperature is to fast the gases produced as a result of the chemical reaction in within the clay and the evaporation of the water could create cracks, deformation, expansion or explosion of the clay [4]. This characteristic of the clay is not always bad, because it is possible to find uses for the resulting expanded clay. The rotary kiln in this work is dedicated to the production of expanded clay particles, for multiple uses, with particle sizes going from 1 mm or less until 1.2 cm of diameter.

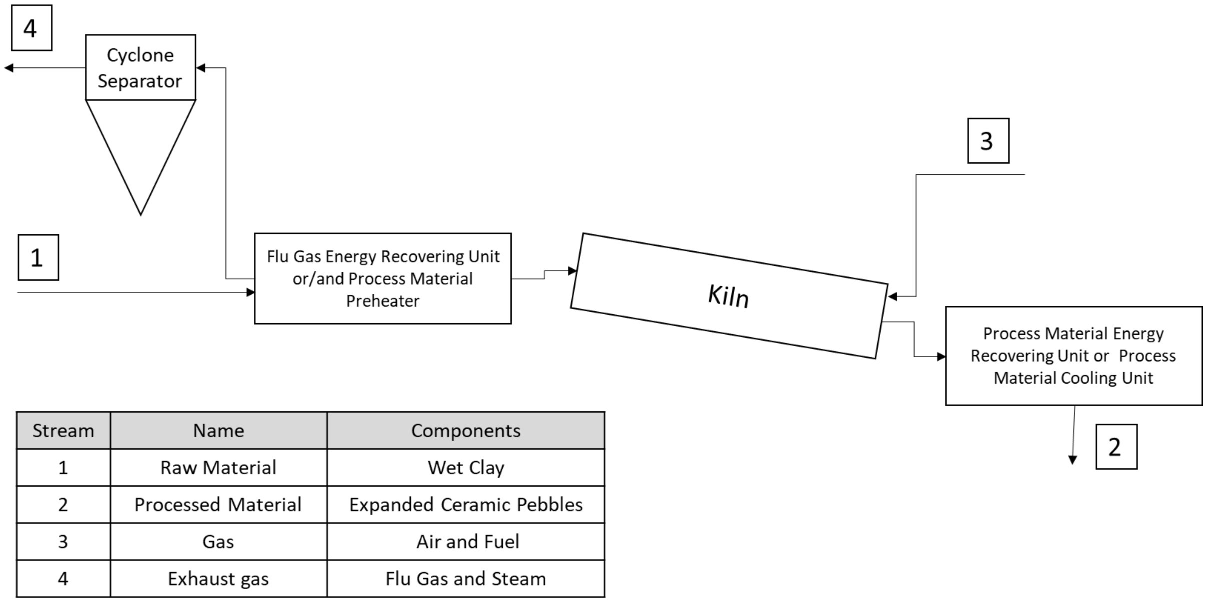
Figure 32; Expanded clay examples [5].

As shown on the figure 15, these clay particles are very porous, amorphous and light. Due to these characteristics they can be used as isolation, fillings, aggregates for concrete, pebbles for the floor decoration, among other usages.

By changing the rotational speed and the inside construction of the kiln as well as the temperature in within of it, the size of the particles can be, although not totally controllable, approached to a determine parameter of sizes.

5.10 Expanded Clay Production Process

From the literature research of Clay/Ceramics and Kilns, it is possible to come with a basic idea of what is necessary to produce expanded clay efficiently, a possible abbreviated process flow diagram is:



Stream	Name	Components
1	Raw Material	Wet Clay
2	Processed Material	Expanded Ceramic Pebbles
3	Gas	Air and Fuel
4	Exhaust gas	Flu Gas and Steam

Figure 33; Kiln Process Diagram [9].

The function of the cyclone separator is to capture possible suspended particles from the flu gas. The function of the first recovering unit or preheater is to reduce the necessary energy for the clay processing or recover some of it in order to use in other process. The kiln is the main equipment and as it was previously mentioned on this work it can be optimize by using isolation to reduce heat losses and by using internal constructions to increase the mass and heat transfer between the gas and solid phase. Finally, the second energy recover unit or processed material cooling unit retrieve remaining energy in the clay.

6 Task Description

This work is based on a real clay mine and processing facility, situated in the region of Karlovy Vary in the Czech Republic. It must be clarified that all the data and parameters of the Kiln are just rough approximations of the real working conditions of this facility. No sensible data or diagram is shown in this work.

As mentioned in the introduction, one of the objectives of this work is to simulate and optimize a kiln, for which a series of basic known parameters are given; these do not only work as a random starting point but most importantly, tie the work closer to the reality, making this work more relevant.

The known parameters are:

1. Kiln inside diameter: 3 meters
2. Kiln Length: 57 meters
3. Inclination to the x axis: 5°
4. Angular Speed: 5 rpm
5. Bed material Feed rate: 5.56 kg/s - 20 ton/h
6. Feed Density: 1760 $^{kg}/_{m^3}$
7. Flue gas speed on the kiln feed intake: 3.7 m/s

6.1 Assumptions and simplification:

1. In most of the real cases the diameter of the kiln changes along its length, usually increasing at the end of it, which in most of the cases is where the burner is located, this has the effect of incrementing the bed surfaces area and therefore the heat transfer becomes more effective, for this work the diameter of the kiln is going to be considered as constant.

2. As the material dries and expands due to the chemical reactions happening within it and the loss of water, the density of the feed material changes along the kiln, usually starting wet and dense and ending its journey inside the rotary oven in a drier and more porous shape. For this work the feed density is going to be considered as constant.

3. No heat exchange will be considered in the simulation. Only the movement of the feed inside the kiln.

4. As the material dries and chemical reactions happen, pyrolytic gases and evaporation gases are realized, in this work, no mass exchange in between phases will be considered.

5. The size of the particles is constant, even though inside of a real kiln the particles can conglomerate or break apart, deepening on the material, rotational speed and temperatures.

6. In order to ease the simulation and increase the mesh quality, the shape of the internal construction will be simplified by modifying it, but always keeping its main function, shape and dimensions.

7. Because of the limitations of the ANSYS software the gravitational force has to be divided into its components generated by the inclination on the rotational axis with respect the X axis, as shown in the following graph:

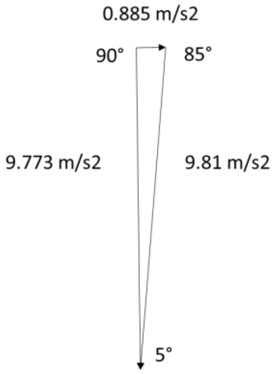


Figure 34; Gravity component vectors for 5-degree inclination.

6.2 Summary

Before having a complete model of the rotary kiln, it is necessary to first understand the movement of the particles inside of it, parameters like response angle, kiln hold up, and residence time are important because they determine quality parameters of the final product. For this reason, it is desirable to find a model than can describe and predict the behavior of these variables.

It is worth mentioning that fluent is not the “go to” option for a simulation of this kind of problems, in most of the articles about this topic, native or other specialized software is used, but due to time limitations and the accessibility of fluent and its tools, it was chosen as the simulation tool.

7 Task Analysis

Before making the simulation its necessary analyze it do identify important values and simplification opportunities.

7.1 Particle mean residence time

Using the selected formulas from the literature research we can estimate the mean residence time. These are the results from the possible formulas:

Formula	Result
Bernard	25.44 Sec
Boateng 1	30.38 Sec
Peray 1	26.06 Sec.
Perry	43.66 Sec.

Figure 35; Resident Time formulas Results

7.2 **Reynolds number for the kiln**

$$Re = \frac{\rho_{gas} v_{gas} D_{kiln}}{\mu_{gas}} = 648{,}416.7 \;\therefore Turbulent\ Region \tag{35}$$

ρ_{gas} is the density of the air $\left[\frac{kg}{m^3}\right]$

v_{gas} is the velocity of the flue gas $\left[\frac{m}{s}\right]$

$D_{kiln}$is the diameter of the kiln [m]

$\mu_{gas}$is the dynamic viscosity of the gas $[Pa \cdot s]$

7.3 Particles flow rate

Assuming the mean particle radius is 3 mm:

$$V_p = \frac{4}{3}\pi {r_p}^3 \tag{36}$$

$$\dot{N_P} = \frac{\dot{m_{clay}}}{V_p \cdot \rho_{clay}} = 27{,}932\ \frac{Particle}{Second}$$

7.4 Number of particles

By multiplying the particle flow rate with the mean residence time, we can estimate the total number of needed particles for the simulation according to each formula:

Formula	Particles
Bernard	710,603
Boateng 1	848,589
Peray 1	727,921
Perry	1,219,533

In order to simplify the simulation and speed its calculation the number of particles per second will be reduced to 60 per time step for the simulation 1 and 2 and to 4 per time step for the simulations 3 and 4 due to their more complex geometry.

7.5 Rotary Kiln Designing

When designing a rotary kiln, it is important to consider what are the parameters that want to be optimize, generally for rotary kiln the heat and mass transfer want to increase. For this objective three variables can be optimizing:

- Residence time
- Relative velocity, particle – flue gas
- Exposed surface area

9.6 Residence time

3 Designs of rotary kiln were made for the following objectives

- Design 1: used on simulation 1 and 2, it is a smooth kiln, with the objectives of testing the simulation methods

- Design 2; used on simulation 3, it is a combination of mixers and dams, in order to mix the feed bed and increase its residence time

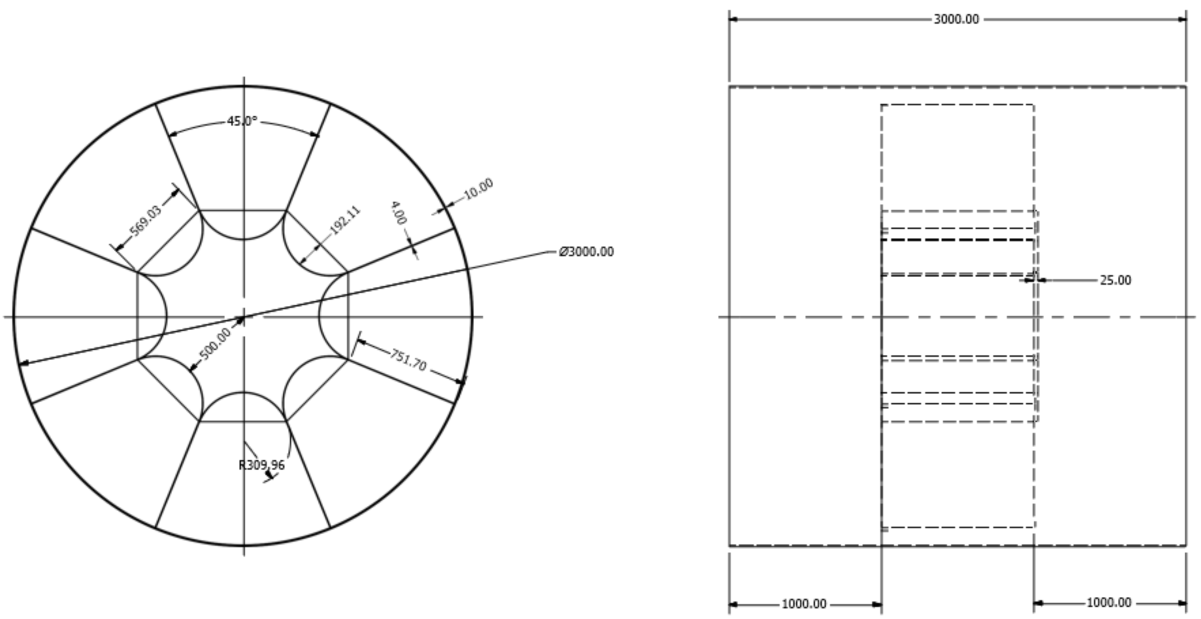


Figure 36; Simulation 3 Geometry

- Design 3: used on simulation 4, it is a combination of hooks and dams, in order to increase the residence time and relative velocity and exposure of the particles to the hot gas.

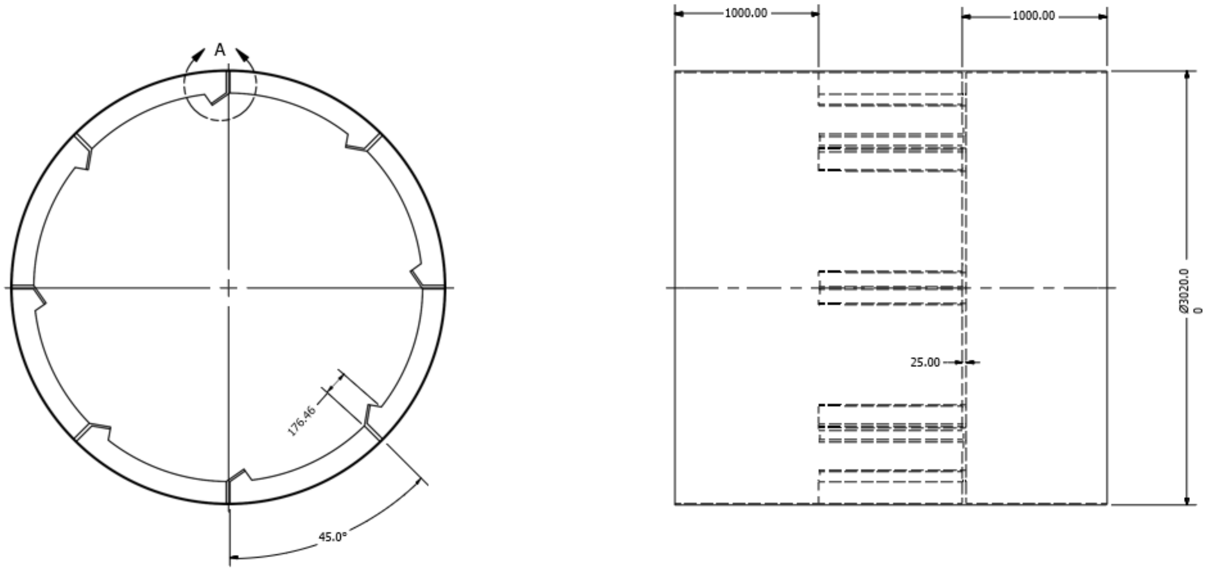


Figure 37; Simulation 4 Geometry

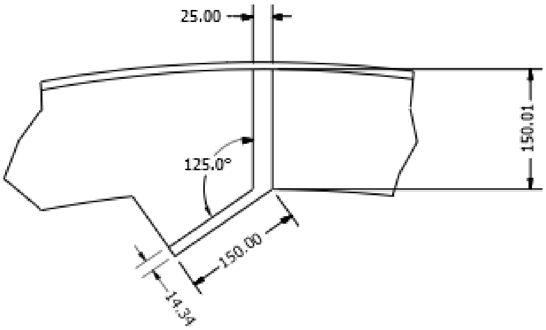


Figure 38; Simulation 4 Geometry 2

The detail description of the kilns can be found on the Annex 2 – Rotary kiln Drawings

8 Fluent Model

Using the ANSYS guide and theory compendium, as well as some of the literature research it was possible to choose a way to simulate a granular material that flows along a rotating wall. The chosen model is described as the following:

8.1 Eulerian Model

The Eulerian multiphase model can be used for the modeling of multiple discrete but interacting phases. The phases can be in any combination and can be used for solid, liquid and gas. Eulerian methods are used to calculate every phase.

When using the Eulerian Multiphase model, the only restrictions for the number of phases present on the system are given by the memory requirements of the model and the convergence behavior. For more complex multi-phase systems, the solution of it will be limited purely by convergence behavior. It is worth mentioning that the Eulerian multiphase model does not differentiate between fluid-fluid and fluid-solid (granular) multiphase flows. A granular phase is defined as one that involves at least one phase that has the characteristic of being composed by macroscopic solid particles.

In the software ANSYS FLUENT the Eulerian Model has the following characteristics

- All Phases share the same pressure
- Each phase has its own set of Momentum and continuity equations
- Each solid phase can have its own defined granular temperature
- Bulk viscosities are obtained by applying kinetic theory to granular flows
- Solid-phase shear is obtained by applying kinetic theory to granular flows
- For the interaction of the phases a drag coefficient is applied
- $k-\varepsilon$ and $k-\omega$ turbulence models are available.

8.2 Eulerian Model Limitations

For the software ANSYS FLUENT the Eulerian Model has the following limitations

- All the phases in the model share a Reynolds Stress turbulence model
- It is not possible to specify mass or volumetric flow rate, it is necessary to do it on flow velocity or on pressure drop terms
- Inviscid flows are not possible
- The simulation of the melting phenomena is not possible
- The simulation of the solidification phenomena is not possible
- Tracking particles in parallel is only possible when the shared memory option is not enabled

8.3 Model Alternatives

In order to achieve the simulation of the rotary kiln there are eight possible ways to do it, depending how the rotation of the system is generated and how the granular flow is simulated. They are as following:

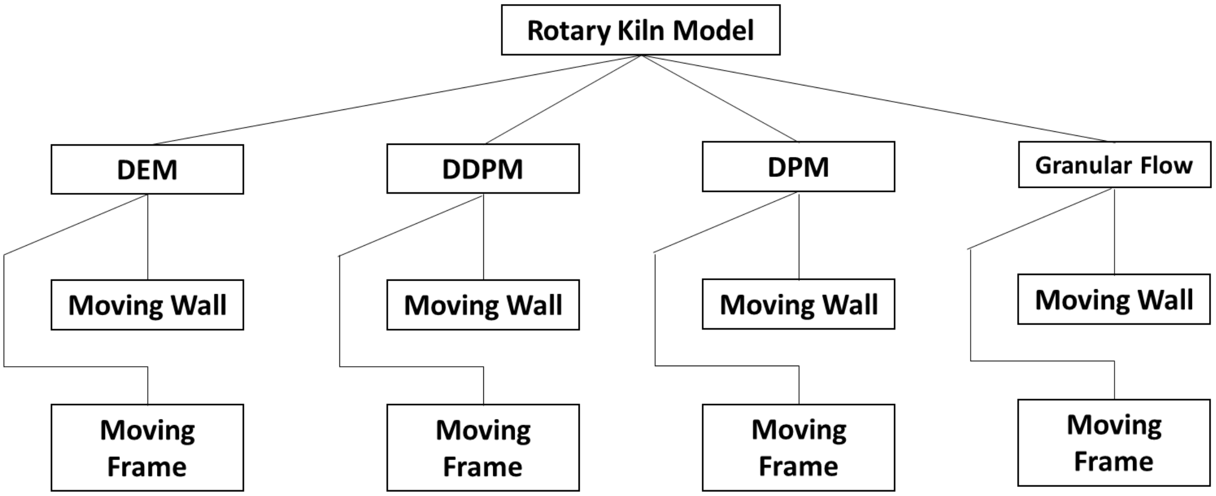


Figure 39; Simulation Models

8.3.1 DEM

The Discrete Element Method or DEM model is the most accurate way to simulate granular flows of big particles, where the shape of it, its material and the interaction it has with the wall and other particles are considered, it is the most realistic approximation that ANSYS offers.

In order to calculate the interactions of the elements in the simulation the DEM model uses a Spring/Dashpot interaction, where the parameters for each material interaction are needed.

This model despite being the most realistic is also the one that is the most expensive on computing power and storage, making it almost exclusive for big research companies or individuals with access to this kind of equipment.

8.3.2 DDPM

The DDPM, Dense Discrete Phase Model, is lighter version of the DEM model where the interactions in between the particles are simplified, to only two values: the normal and the tangential factors. Which determine how much of the energy of the impact is absorbed into heat and how much is used to the bounce.

The model is still complex and allows for simulation of particles of different shapes, lift and drag, particle breaking and aggregation with others. But it doesn’t allow heat transfer simulation by radiation. But it is not possible to obtain the resident time, only the behavior of the feed bed, for obtaining the resident time variable the use of tracer particles is needed

8.3.3 DPM

The DPM, Discrete Phase Model, is the simplest model that keeps the particles as individuals, in this model, only lift drag, and the tangential and normal factors are possible to consider. Despite its simplicity it is able to procedure approximate simulations and it is the one used for the simulation of the rotary kiln in this work. It is in other words the tracer particles with the parameters of the bed material such as: Density, shape and size.

It allows heat exchange simulation by conduction, convection and radiation,

8.3.4Granular flow

This is the most basic way to simulate flows of discrete particles, in this the flow is not simulated as individual particles but as a continuum with the characteristics of the particles, packing limit and granular temperature for example. In this model it is not possible to obtain a particle mean residence time value, only its response angle and general interactions with the walls and boundaries.

8.4.1 Moving wall

By using the rotary wall simulation process, the mesh remains static and only the wall rotates, this makes simulation process easer due to the fact that no special considerations have to be analyzed for the proper working of the intakes and outtakes, rotation and moving axis and references.

8.4.2 Moving Frame

In this case the Mesh itself is rotating or moving, it is less stable to simulate but it is necessary to use when the geometry of the rotating or moving walls is not symmetrical and the interacting in between the particles and the wall is important, which is the case of the work, when the wall of the kiln is not smooth.

8.5 Parameters Needed for the Simulation model.

In order to choose which model to use, it its necessary to count with all the necessary information. On the next chart a caparison of what information is needed per model is shown, marking with a X the minimum necessary, while leaving in blank the one that is not required for the model.

	DEM	DDPM	DPM	Granular Flow
Particle Size Distribution	X	X	X	X
Particle Material	X	X	X	X
Particle Mass Flow Rate	X	X	X	X
Freeboard Gas Mass Flow Rate	X	X	X	X
Kiln Revolution Speed	X	X	X	X
Contact Force Laws – Normal – Spring Dashpot	X			
Contact Force Laws – Tangential – Spring Dashpot	X			
Discrete Phase Reflection Coefficient: Normal	X		X	
Discrete Phase Reflection Coefficient: Tangential	X		X	
Granular Phase Properties		X		X
Phase Interaction Coefficients/models	X	X		

Figure 40; Simulation Models comparison

Not all the models produce the same data, DEM is able to calculate the bed behavior accurately and the mean resident time, DDPM can only calculate the bed behavior accurately, DPM can calculate the resident time and give a bed behavior approximation and Granular flow can only provide a close bed behavior approximation.

It is also important to mention that only the DEM and the Granular flow method are able to be used with a turbulent flow, DDPM and DPM can only work with laminar flow regime.[1]

On this particular case there is a lack of information about the feed material properties, as well as, imitated computing power for these reasons the next models were chosen:

8 .6 Simulation Models

	Simulation 1	**Simulation 2**	**Simulation 3**	**Simulation 4**
DPM	**X**	**X**	**X**	**X**
Granular Flow	**X**			
Moving Frame		**X**	**X**	**X**
Moving Wall	**X**			

Figure 41; Model

It was possible to mix DPM and Granular flow modeling because both techniques do not interact with each other directly, they only required a better mesh quality and smaller time steps to reach the convergence point.

Moving wall modeling doesn't allow the use complex geometries, only cylindrical bodies that rotate along its axis or in cases where the interaction of the material bed with the walls is not important, on this particular work, the interaction of the material bed and the kiln wall is important for that reason simulations 2, 3 and 4 were done using the rotation mesh method.

For more information refer to the Annex 3 -Ansys Equations

9 Simulation

Many simulations where run trying different combinations of settings and modeling, but only the presented four where considered as successful. For a full description of the simulation model direct to Annex 4 – Model Details

9.1 Simulation 1

The geometry for simulation 1 and 2 is the simplest with 3 faces, 2 edges and 2 vertices. Ash shown on the next figure.

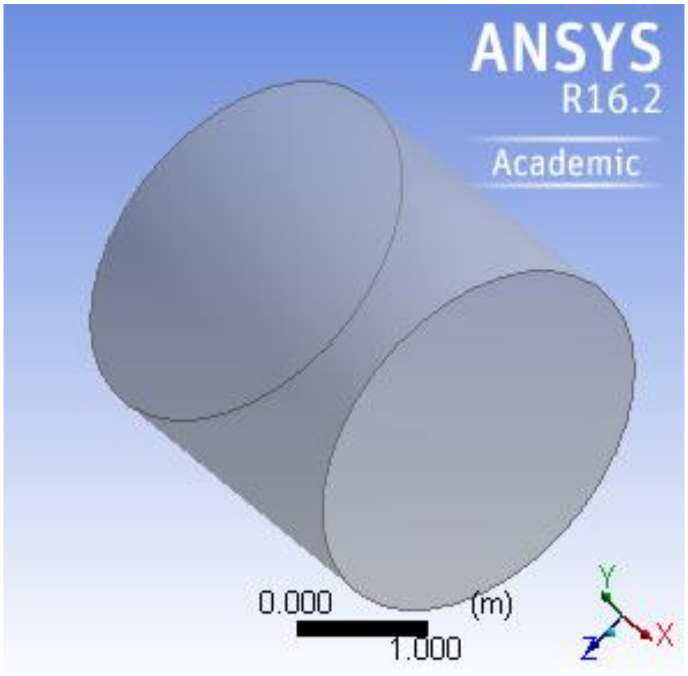


Figure 42; Simulation 1 Geometry Ansys

In order to simulate the granular flow intake, it was necessary to draw a surface on one od the sides of the cylinder, for more details refer to annex 4 – Model Details. This factor made the mesh to be created as shown on the next figure.

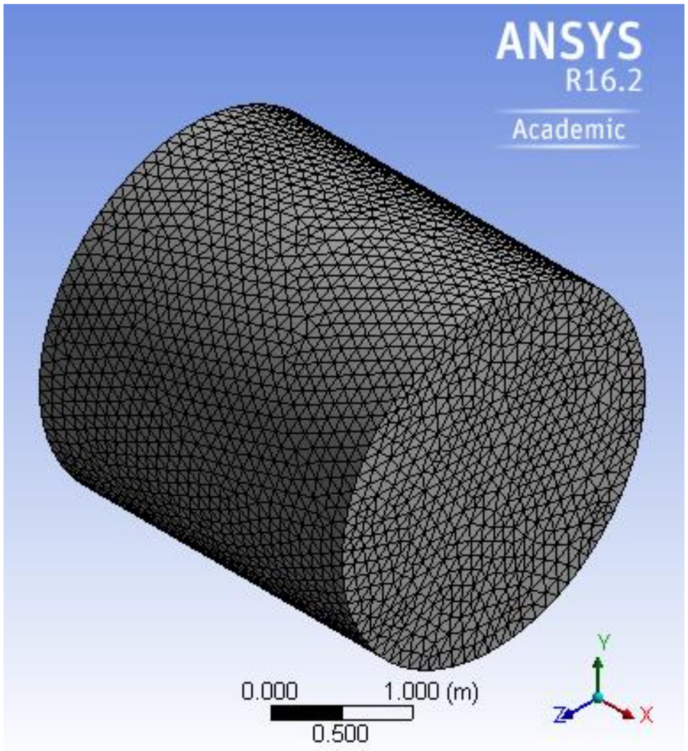


Figure 43; Simulation 1 Mesh Ansys

This mesh has the following orthogonal quality values, shown on the next figure 45:

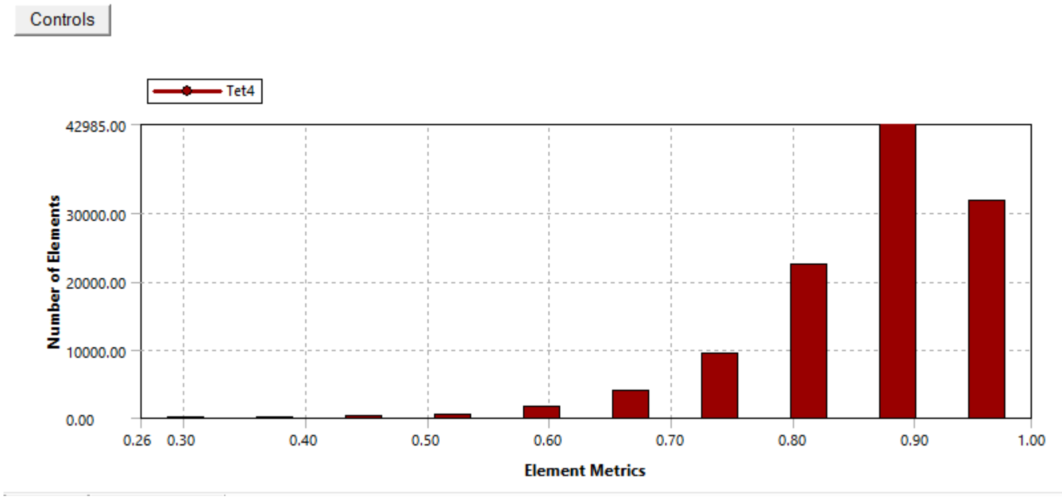


Figure 44; Simulation 1 Orthogonal Quality

- Nodes: 20,684
- Elements: 112,275
- Mesh metrics, orthogonal quality:

- Min 0.26432
- Max: 0.99507
- Average 0.8655
- Standard Deviation: 8.39874e-002

And a under the skewness measurement, as shown on the next figure:

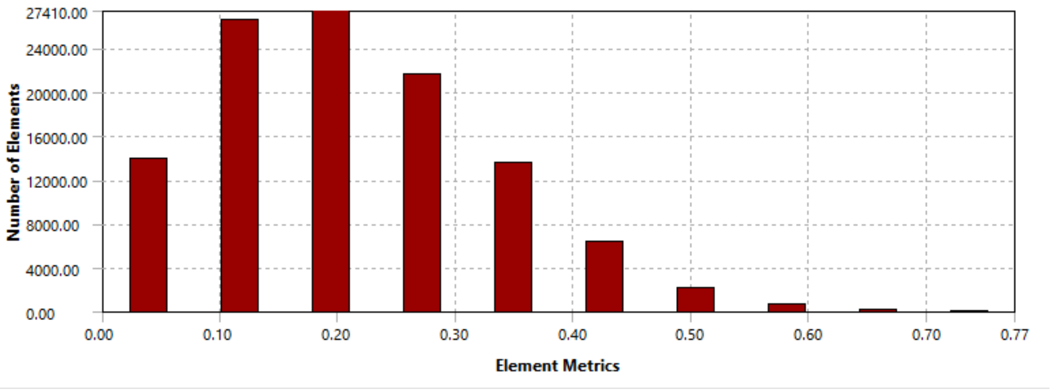


Figure 47; Figure 45; Simulation 1 Mesh Skewness

- Min: 5.952e-006
- Max: 0.77462
- Average: 0.2113
- Standard Deviation: 0.1168
-

The simulation was Run for 100 seconds with a time step of 0.1 Seconds and 20 interactions per time step. As shown on the next figure

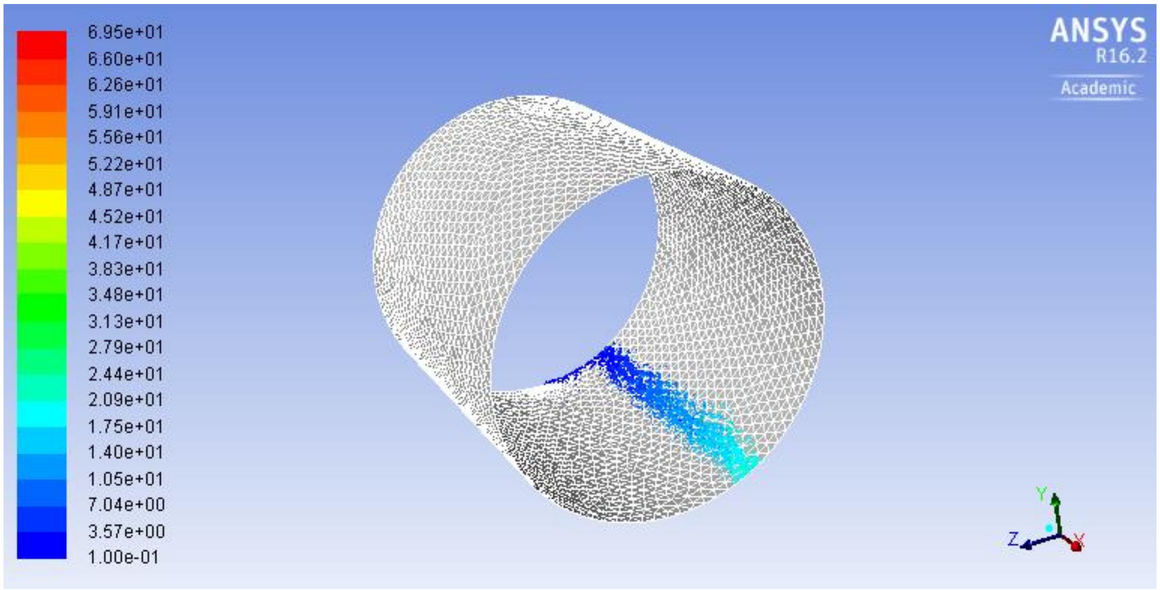


Figure 46; Simulation 1 Particle Flow

9.2 Simulation 2

This simulation uses the same geometry as simulation one.

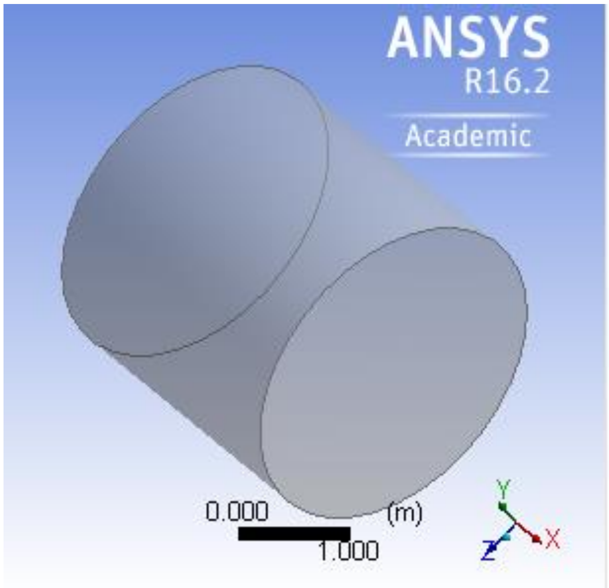


Figure 47; Simulation 2 Geometry Ansys

In this case, it wasn’t necessary to create an inlet surface for the clay granular flow, this allows the mesh to be created as shown on the next figure 48:

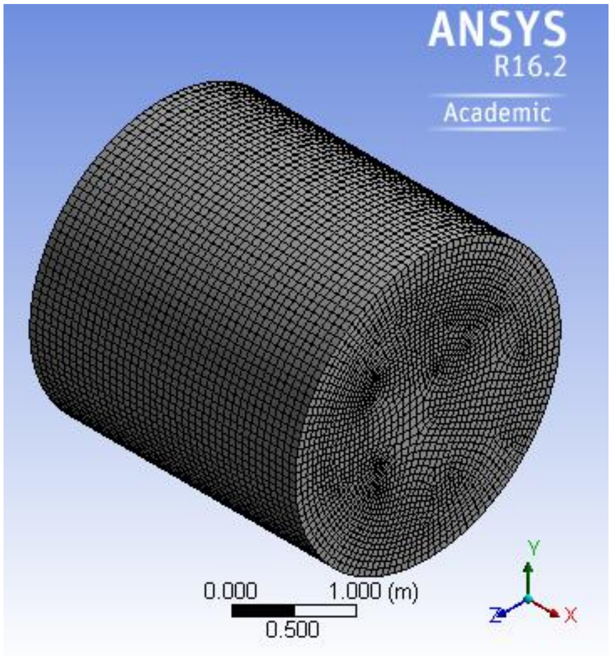


Figure 48; Simulation 2 Mesh Ansys

This mesh has the following orthogonal quality values, shown on the next figure:

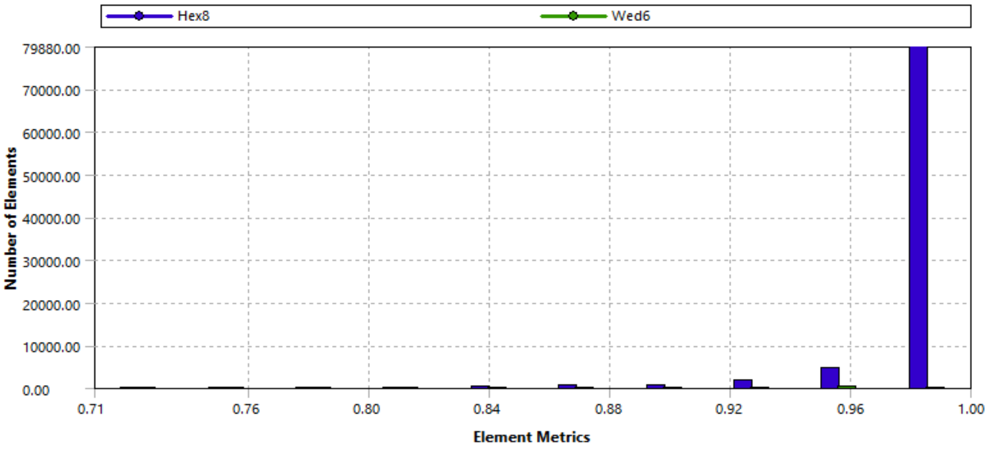


Figure 49; Simulation 2 Orthogonal Quality

- Nodes: 92,742
- Elements: 88,120
- Mesh metrics, orthogonal quality:
- Min 0.70895
- Max: 0.9999
- Average 0.9891
- Standard Deviation: 2.2534e-002

And a under the skewedness measurement, as shown on the next figure:

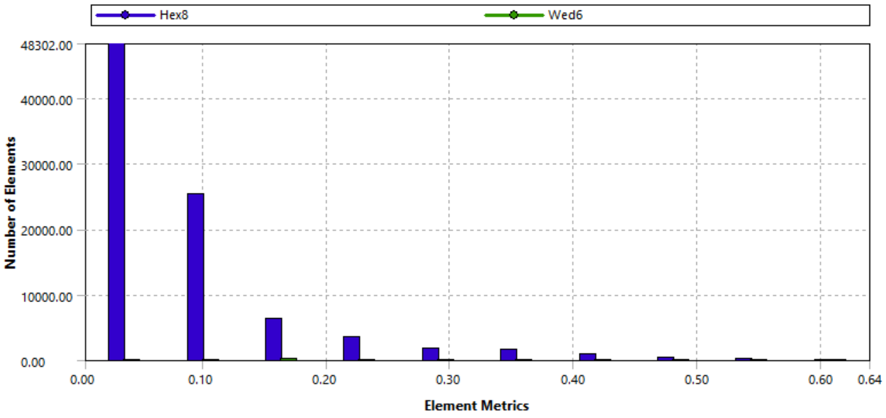


Figure 50; Simulation 2 Mesh Skewness

- Min: 4.8263e-003
- Max: 0.63981
- Average: 8.8145e-002
- Standard Deviation: 8.0409e-002

The simulation was Run for 100 seconds with a time step of 0.005 Seconds and 25 interactions per time step.

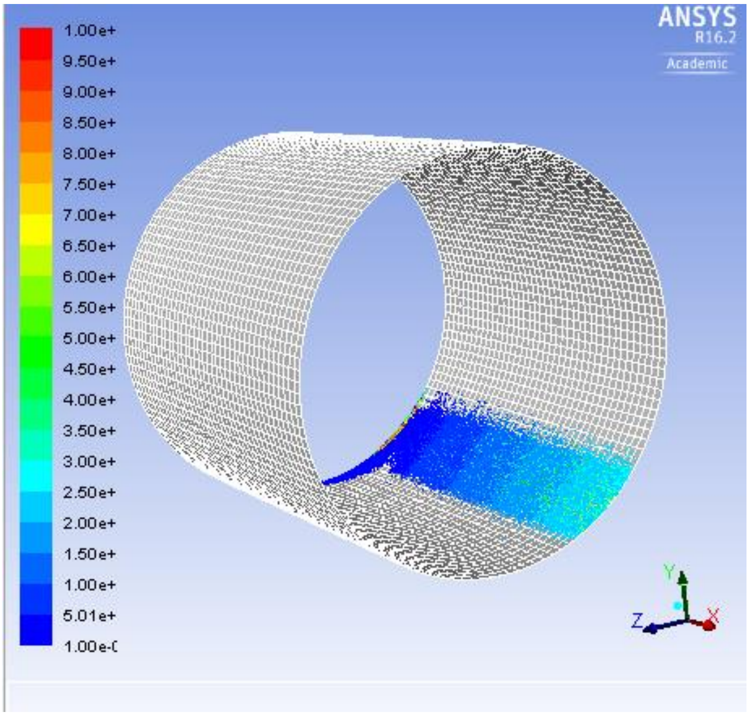


Figure 51; Simulation 2 Particle Flow

9.3 Simulation 3

The geometry for simulation 3 is very complicated with 46 faces, 132 edges and 84 vertices.

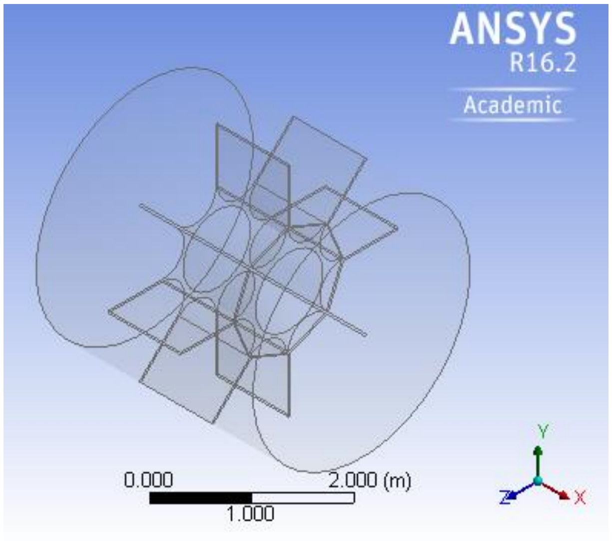


Figure 52; Simulation 3 Geometry Ansys

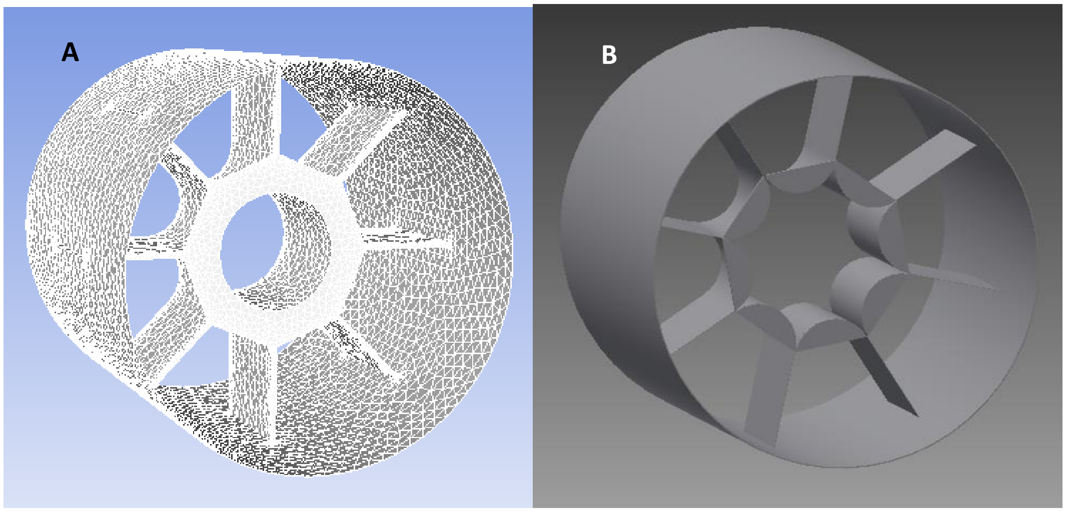


Figure 53; Comparison in between 3D model and Fluent model.

As shown in the previous figure 33, the side B represent a section of the real kiln, with length of 3 meters and diameter of 3 meters, the shape of the internal construction is a one of the possible designs, the Diagram A is the meshed wall used for the Fluent simulation where the edged of the inside were smoothed, using a simple cylinder instead of a star alike shape. This change on the geometry was made in order to reduce the number of cells in the mesh as well to improve its quality.

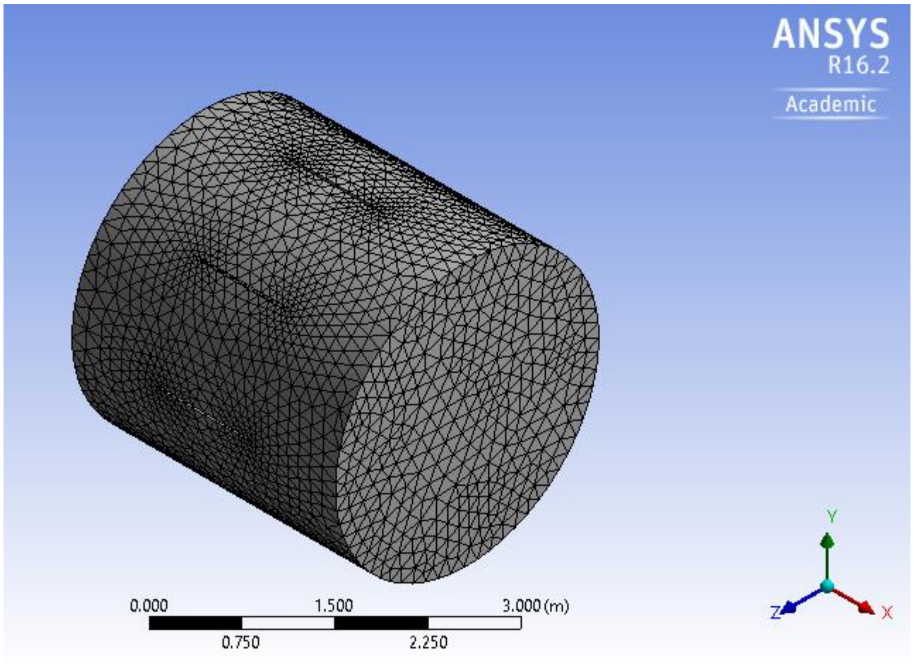


Figure 54; Simulation 3 Mesh Ansys

This mesh has the following orthogonal quality values, shown on the next figure:

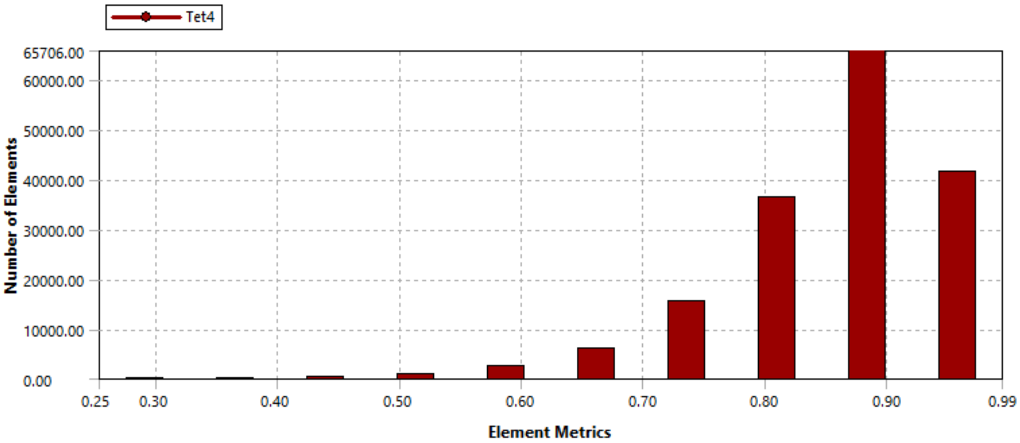


Figure 55; Simulation 3 Orthogonal Quality

- Nodes: 31,011
- Elements: 158, 589
- Mesh metrics, orthogonal quality:
- Min 0.25293
- Max: 0.99473
- Average 0.85719

- Standard Deviation: 8.5086e-002

And a under the skewedness measurement, as shown on the next figure

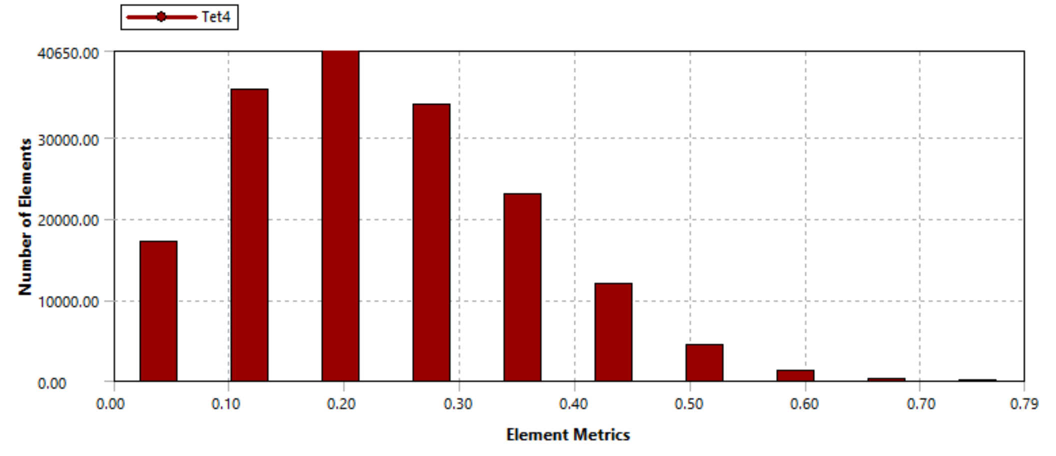


Figure 56; Simulation 3 Mesh Skewness

- Min: 1.0801e-004
- Max: 0.7896
- Average: 0.23058
- Standard Deviation: 0.12201

The simulation was Run for 100 seconds with a time step of 0.01 Seconds and 25 interactions per time step.

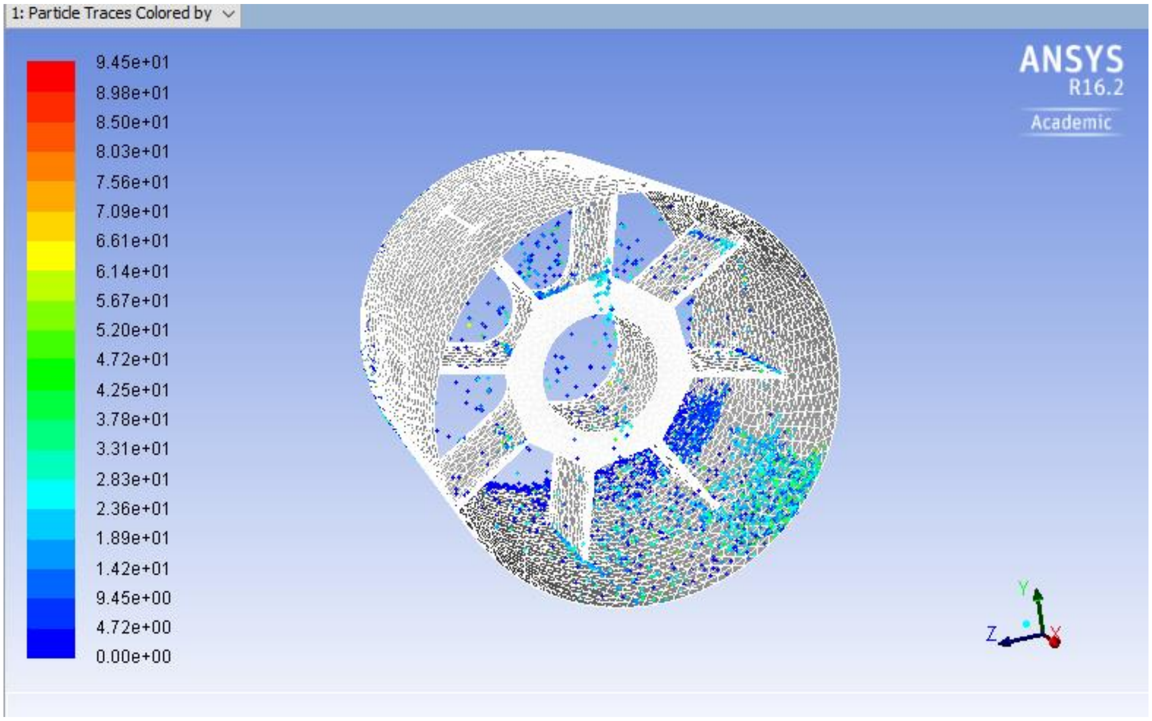


Figure 57; Simulation 3 Particle Flow

9.4 Simulation 4

The geometry for simulation 3 is the most complicated with 105 faces, 276 edges and 180 vertices

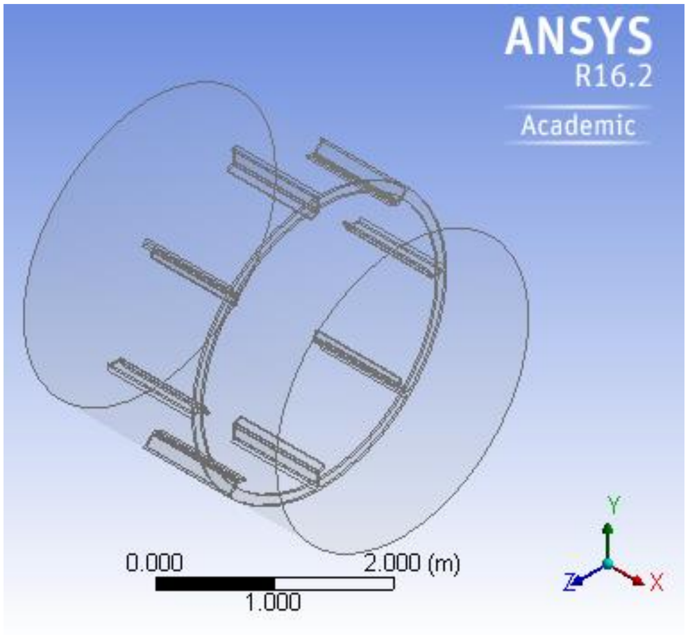


Figure 58; Simulation 4 Geometry Ansys

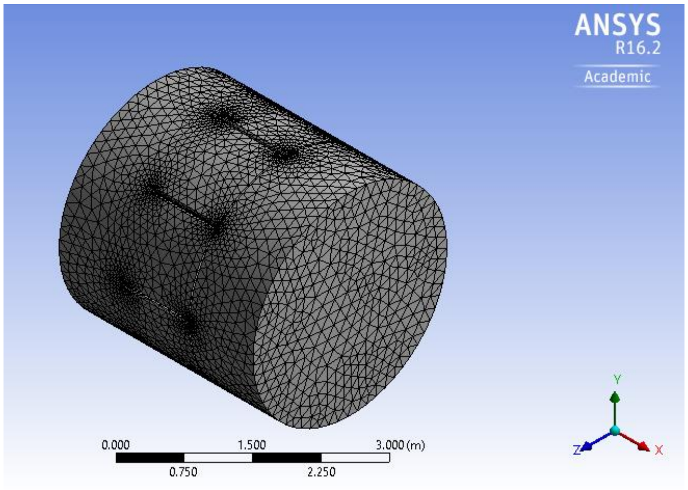


Figure 59; Simulation 4 Mesh Ansys

This mesh has the following orthogonal quality values, shown on the next figure:

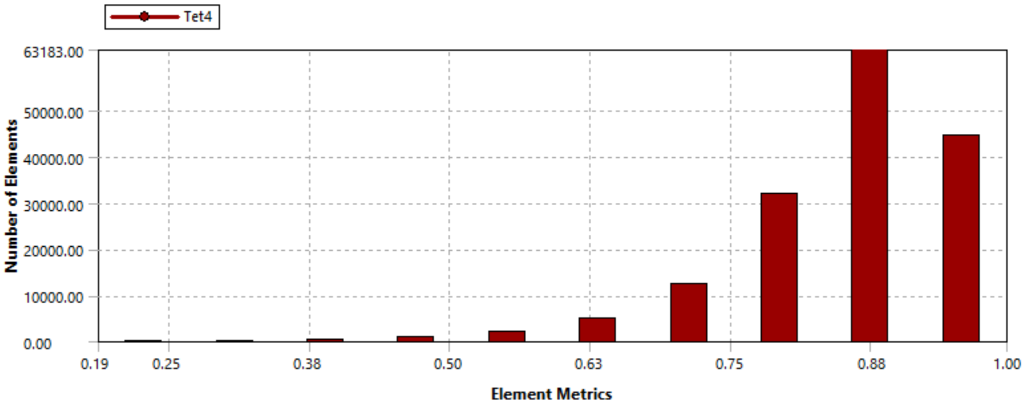


Figure 60; Simulation 4 Orthogonal Quality

- Nodes: 30,173
- Elements: 159, 940
- Mesh metrics, orthogonal quality:
- Min 0.18692
- Max: 0.99566
- Average 0.85304
- Standard Deviation: 9.2512e-002

And a under the skewedness measurement, as shown on the next figure:

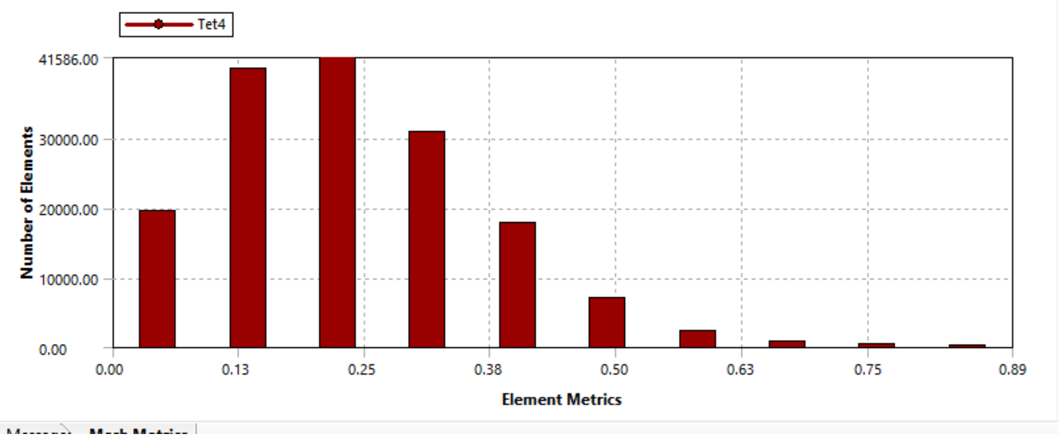


Figure 61; Simulation 4 Mesh Skewness

- Min: 3.9097e-004
- Max: 0.89364
- Average: 0.23707
- Standard Deviation: 0.13009

The simulation was Run for 100 seconds with a time step of 0.005 Seconds and 25 interactions per time step.

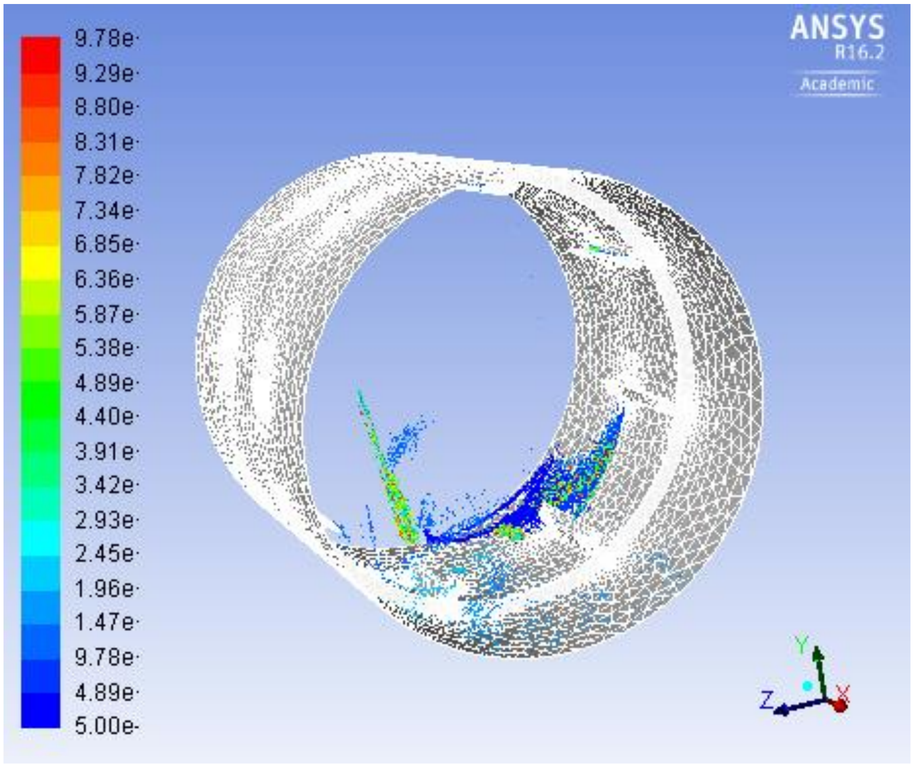


Figure 62; Simulation 4 Particle Flow

10. Results

10.1 Simulation 1

The simulation of the rotary kiln was run for a hundred seconds or approximately five times the mean residence time of the particles, in order to stabilize it and to obtain more accurate results. After that forty-two samples of the particles exiting the geometry were taken with an interval of a tenth of a second, or in odder words the samples were taken in a lap of five seconds.

From this, 2521 particle diameter and particle residence times samples were extracted, then all the data for residence time was analyze on the software Easyfit to find the probabilistic distribution that fit most of the data, then particles were segmented by diameter and the same analysis was performed to find the probabilistic distribution and the derivate data from it according each diameter. The following normal probability density function is the resulting one:

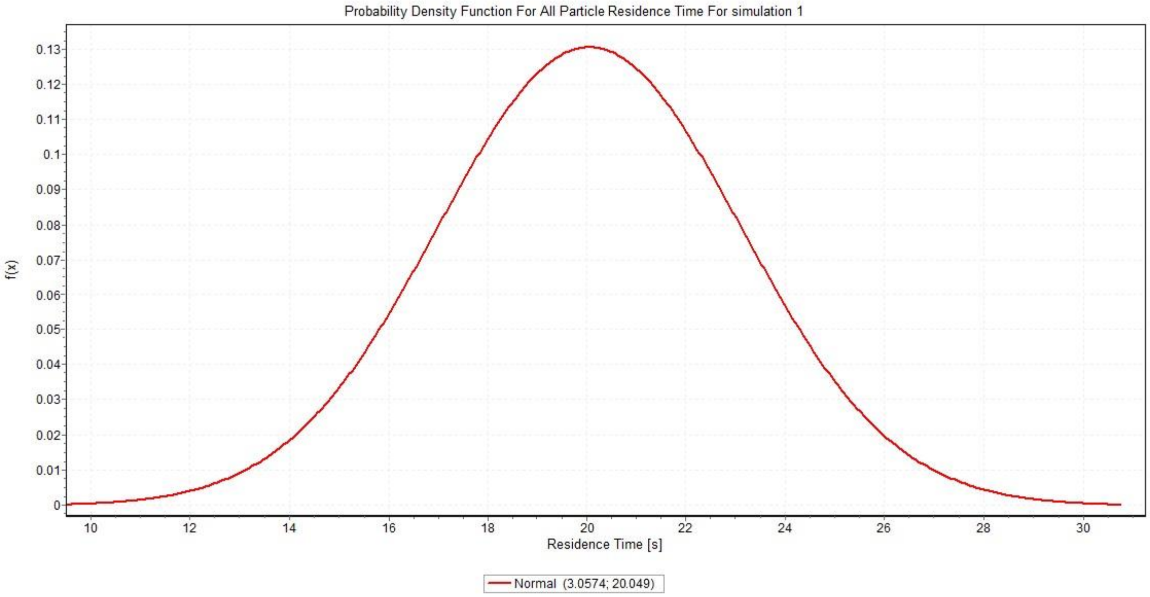


Figure 63; Simulation 1 particle size normal distribution

Parameter	Value
Mode	**20.049**
Mean	**20.049**
Variance	**9.3479**
St. Dev.	**3.05474**
Coef. Of Var.	**0.1525**

Figure 64; Simulation 1 particle size normal distribution parameters

From the mean residence time of each particle diameter is possible to generate the following figure

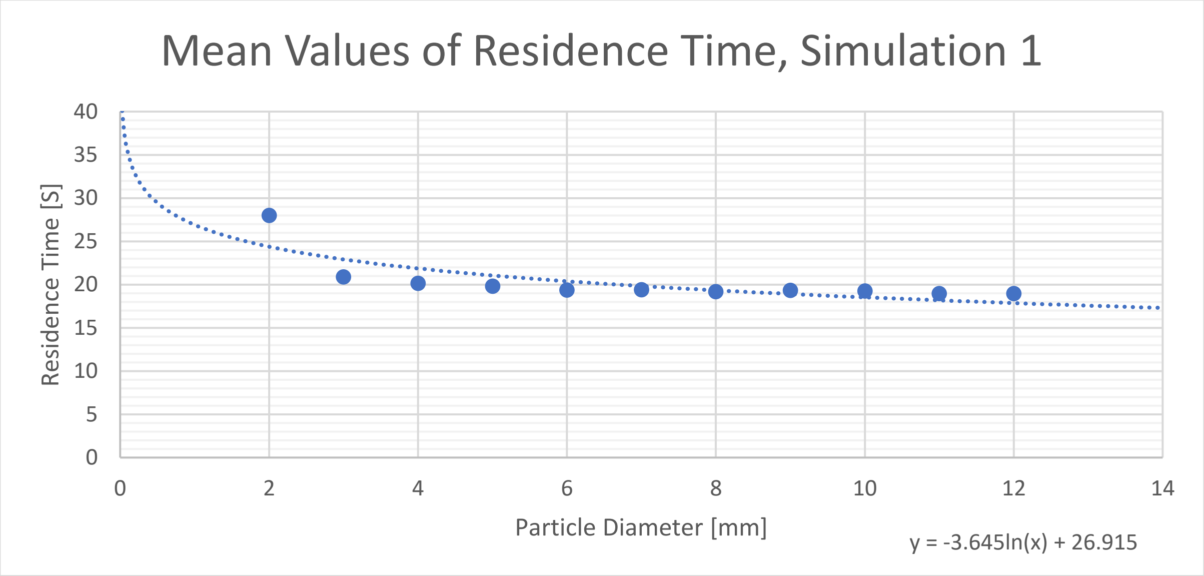


Figure 65; Mean Values of Residence Time, Simulation 1

10.2 Simulation 2

The simulation of the rotary kiln was run for a hundred seconds or approximately four times the mean residence time of the particles, in order to stabilize the it and therefore obtain more accurate results. After that, 6 samples of the particles exiting the geometry were taken with an interval of a tenth of a second, or in odder words the samples were taken in a lap of five seconds.

From this, 2440 particle diameter and particle residence times samples were extracted, then all the data for residence time was analyze on the software Easyfit to find the probabilistic distribution that fit the most to the data, then particles were segmented by diameter and the same analysis was performed to find the probabilistic distribution and the derivate data from it according each diameter

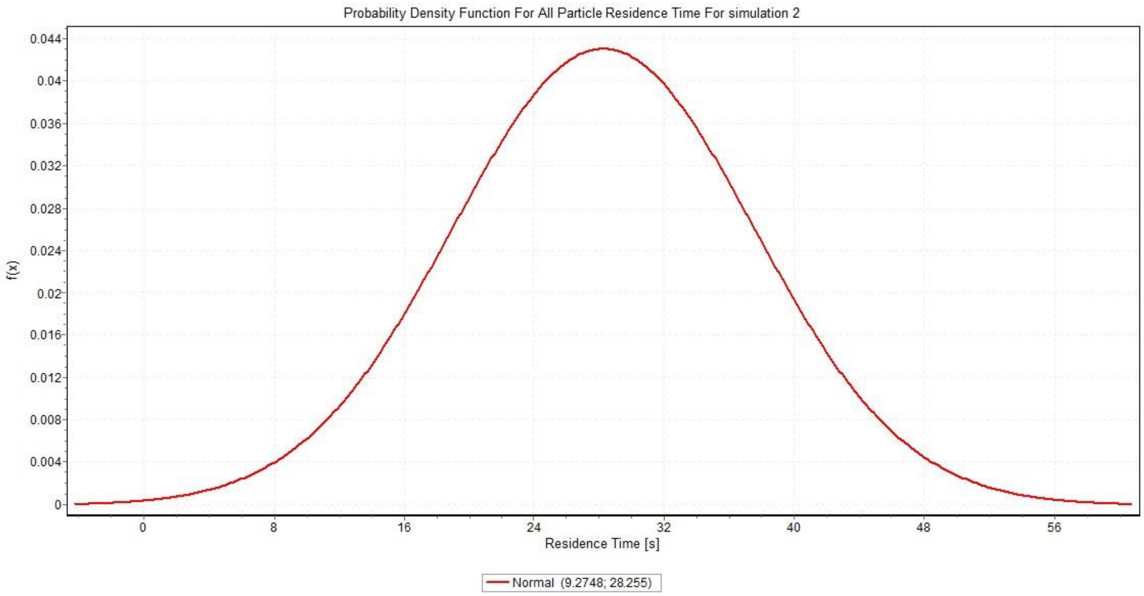


Figure 66; Simulation 2 particle size normal distribution

Parameter	**Value**
Mode	**28.225**
Mean	**28.225**
Variance	**86.021**
St. Dev.	**9.2748**
Coef. Of Var.	**0.32825**

Figure 67; Simulation 2 particle size normal distribution parameters

From the mean residence time of each particle diameter is possible to generate the following figure

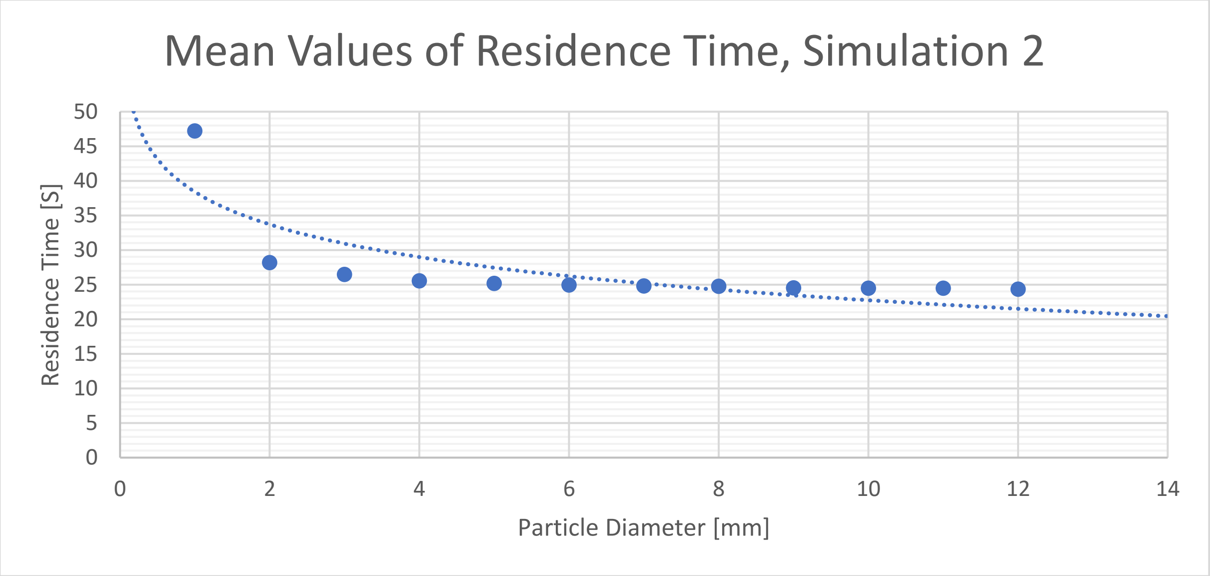


Figure 68; Mean Values of Residence Time, Simulation 2

10.3 Simulation 3

The simulation of the rotary kiln was run for a hundred seconds or approximately four times the mean residence time of the particles, in order to stabilize the it and therefore obtain more accurate results. After that 15 samples of the particles exiting the geometry were taken with an interval of a tenth of a second, or in odder words the samples were taken in a lap of five seconds.

From this, 310 particle diameter and particle residence times samples were extracted, then all the data for residence time was analyze on the software Easyfit to find the probabilistic distribution that fit the most to the data, then particles were segmented by diameter and the same analysis was performed to find the probabilistic distribution and the derivate data from it according each diameter

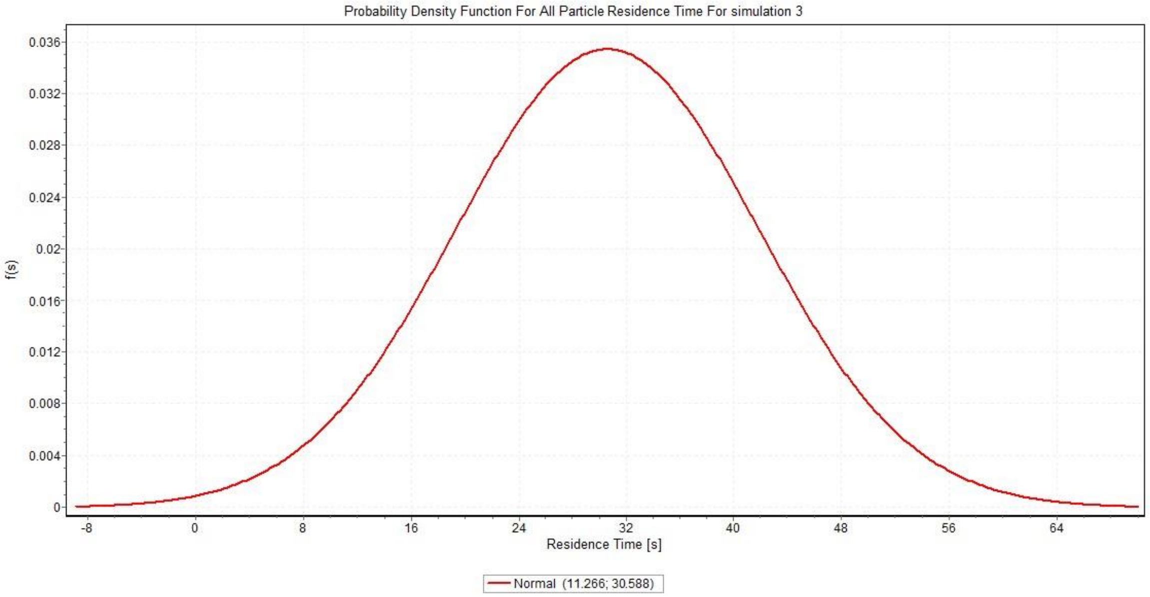


Figure 69; Simulation 3 particle size normal distribution.

Parameter	**Value**
Mode	**30.588**
Mean	**30.588**
Variance	**126.92**
St. Dev.	**11.266**
Coef. Of Var.	**0.36832**

Figure 70; Simulation 3 particle size normal distribution parameters

For this simulation there are not enough points for making a correlation analysis for the particle diameter vs particle mean residence time.

10.4 Simulation 4

The simulation of the rotary kiln was run for a hundred seconds or approximately four times the mean residence time of the particles, in order to stabilize it and therefore obtain more accurate results. After that 20 samples of the particles exiting the geometry were taken with an interval of a tenth of a second, or in other words the samples were taken in a lap of five seconds.

From this, 304 particle diameter and particle residence times samples were extracted, then all the data for residence time were analyze in the software Easyfit to find the probabilistic distribution that fit the most to the data, then particles were segmented by diameter and the same analysis was performed to find the probabilistic distribution and the derivate data from it according each diameter

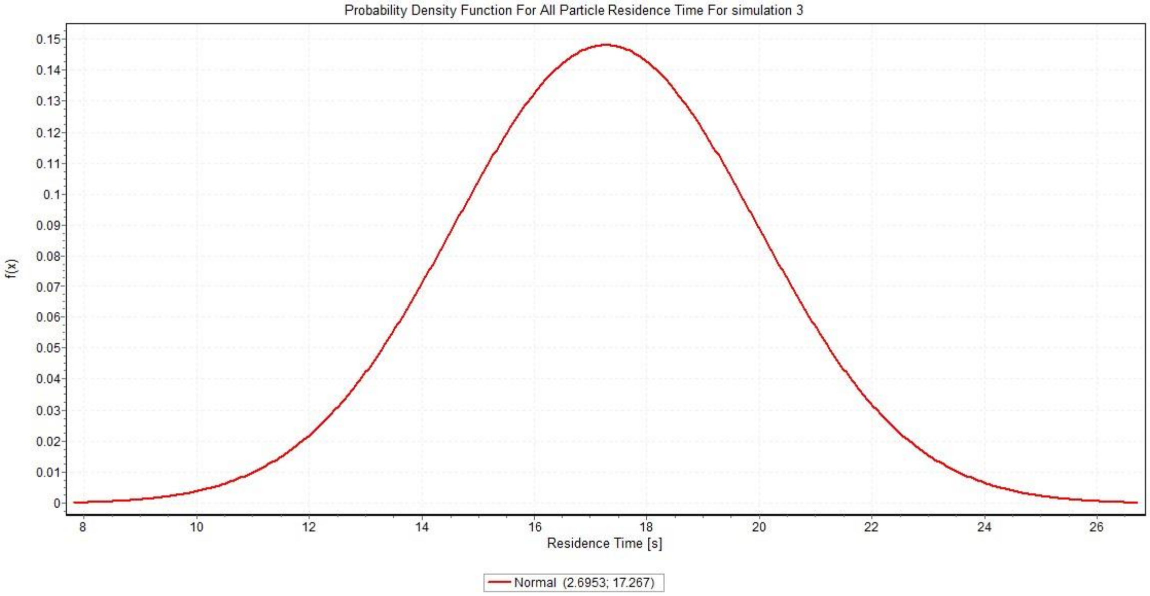


Figure 71; Simulation 4 particle size normal distribution.

Parameter	**Value**
Mode	**17.267**
Mean	**17.267**
Variance	**7.2649**
St. Dev.	**2.6953**
Coef. Of Var.	**0.1561**

Figure 72; Simulation 4 particle size normal distribution parameters

11 Results Comparison

From the regression analysis of the results of the four simulations it is possible to obtain an equation to predict the mean residence time of the particles, using the particle diameter as input variable, these equations are only valid for kilns of 3 meters length and 3 meters in diameter, a feed material density of 1,760 $^{kg}/_{m^3}$ and a countercurrent flow of air of 3.7 m/s at standard temperature. These are the following:

Simulation 1

$$\tau = -3.645 \ln D_P + 26.915 \quad [s] \tag{38}$$

Simulation 2

$$\tau = -6.801 \ln D_P + 30.407 \quad [s] \tag{39}$$

It is worth mentioning that all the generated formulas match closely with the formulas found on the literature search. As the next chart shows:

Formula	**Result**
BERNARD	25.44 Sec
BOATENG 1	30.38 Sec
PEARY 1	26.06 Sec.
PERRY	43.66 Sec.
Simulation 1	20.049 Sec.
Simulation 2	28.225 Sec.

Figure 73; Results Comparison.

It is possible to appreciate that the value predicted by Peary formula and the Simulation 2 match.

The simulation 2 method seems to be more accurate because it matches the calculated results closely.

From the simulation 1 six granular phases were simulated in order to predict the behavior of the bed: Depth and response angle:

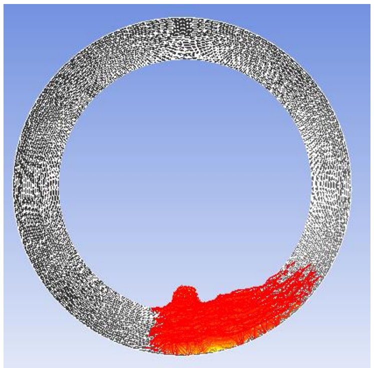


Figure 74; simulation response angle.

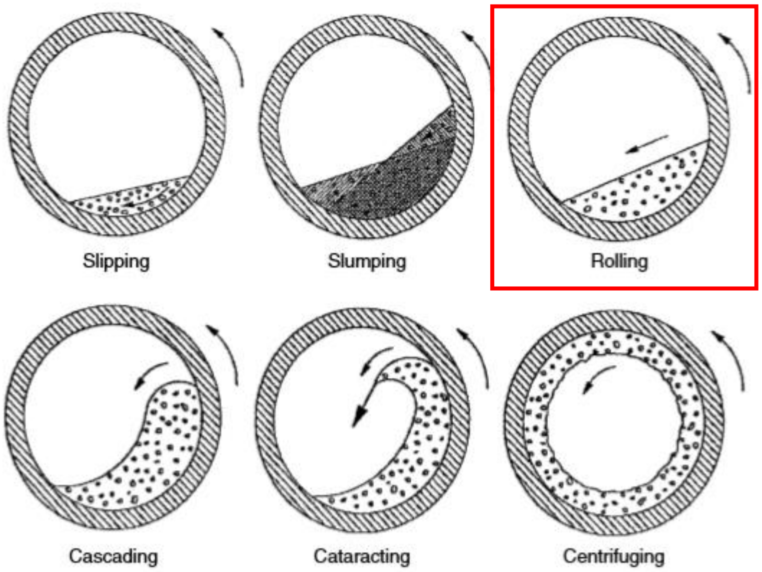


Figure 3; Froude number meaning diagrams. [3]

If we calculated the Froude number it is possible to see the behavior of the simulated bed matches the expected from the formula:

$$Fr = \frac{\omega^2 R}{g} = \frac{0.08333^2 \cdot 1.5}{9.81} = 1.06x10^{-3} \quad \therefore \quad Rolling \tag{40}$$

It is possible to see from the figures 36 and 151, the behavior of the bed matches.

Depside the model simplifications, from the mean residence time similarities and the behavior of the bed it is possible to conclude that the simulations can be used to predict and experiment with the optimization of a rotary kiln.

12 Conclusions

1.- Fluent is able to simulate a rotary kiln, but it has its restrictions, for instance it is necessary to have a computer with very high computing power. For instance, if all the particles in the bed feed are simulated, the number of elements would go to the order of millions and calculation time per time step as well as reading and processing the obtain data would increase drastically, almost to the point of unworkable, for this reason simplifications like a reduction on the particles flow rate, geometry, time step and mesh size had to be done. This will decrease the accuracy and reliability of the simulation, a therefore a balance between required computational power, processing time and accuracy has to be done. This balance would be given according to each individual case.

2.- The movement of the particles inside of a rotary kiln is dictated by very complex laws plus the great number of variables that must be considered and the transient nature of it, make almost impossible to come with an analytical solution, most of the available solutions are derivate from experiments, that limits the proposed solutions to certain parameters like, kiln shape and size, particle size and material. For this reason, none of the founded solutions for calculation of the mean residence time agree with each other but all of them lay in a range of 26 seconds of difference.

3.- The hooks and dam combination decrease the residence time, despite the belief that the dam would have the opposite effect. This happened due to the effect of the hooks that can be observed on the simulation, the hooks lift the particles and when they are dropped advance along the kiln axis faster due to the fact that that they are realized from the particle traffic, in other words instead of being trapped on the particle flow of the bed they are free to advance along the axis specially if the inclination of the kiln is high and the dam low enough. The benefit of the hooks is that they increase the relative velocity of the gas versus the particle as well as increase the exposed surface of the particles to it, and as a result of this the heat and mass exchange would increase, making the kiln more efficient.

4.- There are many literate sources but they either to specific about kiln geometry, processed material or they use specialized, native, software to calculate the behavior of the kiln system, making them almost useless if the kiln and material parameters are different or there is no possibility to access the used software.

5.- The most accurate way to simulate a rotary kiln would be by the use of the DEM model and moving mesh, because those are the most accurate ways to simulate the behavior of a discrete granular flow and its interaction with the walls. This simulation method also allows the inclusion of heat transfer by all the possible ways; conduction, convection and radiation.

6.- Eight possible ways to simulate a rotary kiln were explored and mentioned in this work. Only the two simplest ones; DPM and Granular flow, were put into practice. Limitations on the computing power play an important role on the decisions that have to be made for choosing a model, as well as assumptions and simplifications making.

7.- Simulation 2 has a 40% larger mean residence time than 1, more research about the reasons for this, has to be done on the impact and optimal setting of moving wall and moving mesh methods.

8.- Comparing the Simulation 2 and 3, both DPM and moving mesh methods, the increase of residence time was 8.22% as well as a total disruption of the particles flow along the kiln, both objectives of increasing residence time and mixing the flow were achieved.

9.- Comparing the Simulation 2 and 4, both DPM and moving mesh methods, the decrease of residence time was 38.22%. only the hooks wanted action was achieved, more simulation with a higher dam or one in a different location is needed.

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List of Figures

List of equations

List of Symbols

Symbols Used		
A	Heat transfer area per unit kiln length	m
a_b	Effect thermal diffusivity	$\frac{m^2}{s}$
B	Material Size Constant	-
C	Correction factor	-
c_p	Specific heat capacity	$\frac{kJ}{kg \cdot K}$
D	Kiln Diameter	Meters, m
D_e	Equivalent diameter	m
d_p	particle diameter	Millimeters, mm
E	Radiometric force	$\frac{W}{m^2}$
F	Feed rate	${}^{kg}/_{hr}$
F	Feed velocity	$\frac{k}{hr\ m^2}$
Fr	Froude number	-
G	freeboard gas velocity	$\frac{kg}{hr\ m^2}$
g	gravity	$\frac{m}{s^2}$
Gr	Grasholf Number	-
H	Damn Height	Meters, m
h	Heat transfer coefficient	$\frac{W}{m^2 \cdot K}$
J	Effective radiation	$\frac{W}{m^2}$

k	Thermal conduction coefficient	$\frac{W}{m \cdot K}$
L	Kiln Length	Meters, m
L_c	length of the chord	m
l_w	Exposed wall circumference	m
$\dot{m}$	Mass flow rate	$\frac{m}{s}$
N, n	Revolutions per Minute	RPM
N_c	Cascades per revolution	Cascades per revolution
Nu	Nusselt number	-
Pe	Peclet Number	-
Pr	Prandtl Number	-
r	Kiln radius	m
Re	Reynolds number	-
s	Slope	${}^{m}/_{m}$
SV	Space Velocity	$\frac{ton}{m^3 day}$
T	Temperature Absolute	T
u_{ax}	Mean axial velocity	${}^{m}/_{s}$
$\dot{V}$	Volumetric flow rate	${}^{m^3}/_{s}$
z_o	axial movement of the particle per cascade	m

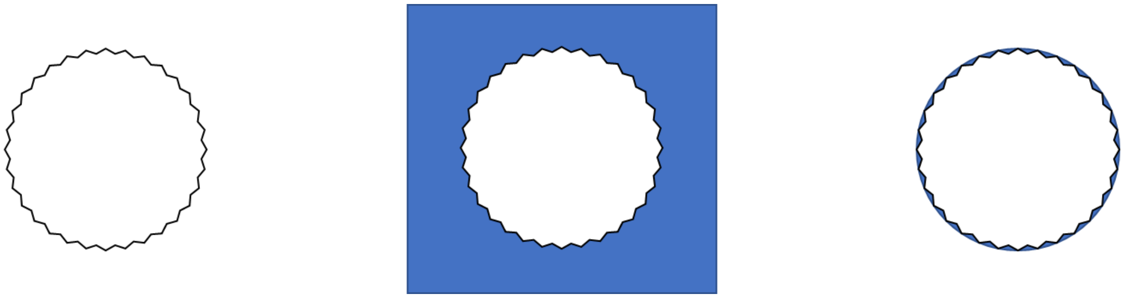
Greek Symbols		
α	Volumetric Phase ratio	%
β	inclination of the kiln on the horizontal axis	Degree

θ	inclination of the kiln	Degree
μ	Dynamic viscosity	$Pa.s$
π	Pi	-
ρ	Density	$\frac{kg}{m^3}$
τ	Mean Residence time	Hour, Min, sec
ϕ	Static angle of repose of material or Kiln slope in angular measure	Degree
φ	fraction of cross section occupied	%
ψ	bed angle relative to the axial plane	degree
ω	Angular velocity	1/sec

ANNEX 1 - Ceramic Properties

Density

The density of the final ceramic product is related to the composition of the raw materials and the heat processes of transformation from clay to ceramic. It is necessary to measure it, as well as its porosity. For such task it is possible to use the following procedure.



Using the Archimedes principle, it’s possible to say [4]:

$$Mass\ of\ Displaced\ Liquid \quad m = m_W - m_L \quad [kg]$$

$$Density\ of\ \ Liquid \quad D\ \left[\frac{kg}{m^3}\right]$$

$$Volume\ of\ Displaced\ Liquid \quad v = \frac{m_W - m_L}{D} \quad [m^3]$$

$$Open\ pore\ volume \quad OPV = \frac{m_W - m_D}{D} \quad [m^3]$$

$$Percentage\ of\ open\ porosity \quad POP = \frac{m_W - m_D}{m_W - m_L} \times 100 \quad [-]$$

Figure 30; Density measuring, formulas.

Hardness

There are two kind of possible hardness measurements - scratch and indentation. This property depends on factors as crystalline structure and firmness of the bonds.

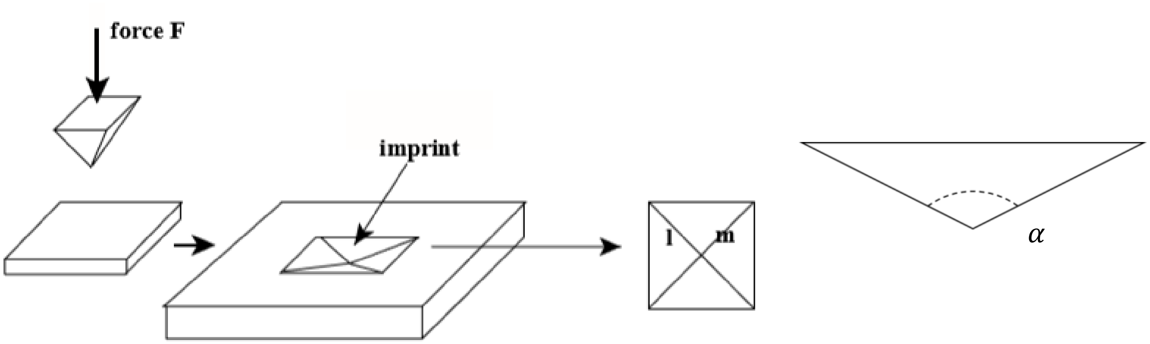
- Scratch Hardness

  A specially made Stylus with a special shape and determined material is passed against the surface of the measured material, if the stylus does not scratch the surface another is used with a different harder material []. This kind of property is compared versus the Mohs scale.

Mineral	Hardness
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Feldspar	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

Mohs Scale. [4]

- Indentation Hardness



Indentation Hardness. [4].

$$A = \frac{a^2}{2 \cdot \sin\left(\frac{\alpha}{2}\right)}$$

In which

$$a = \frac{l + m}{2}$$

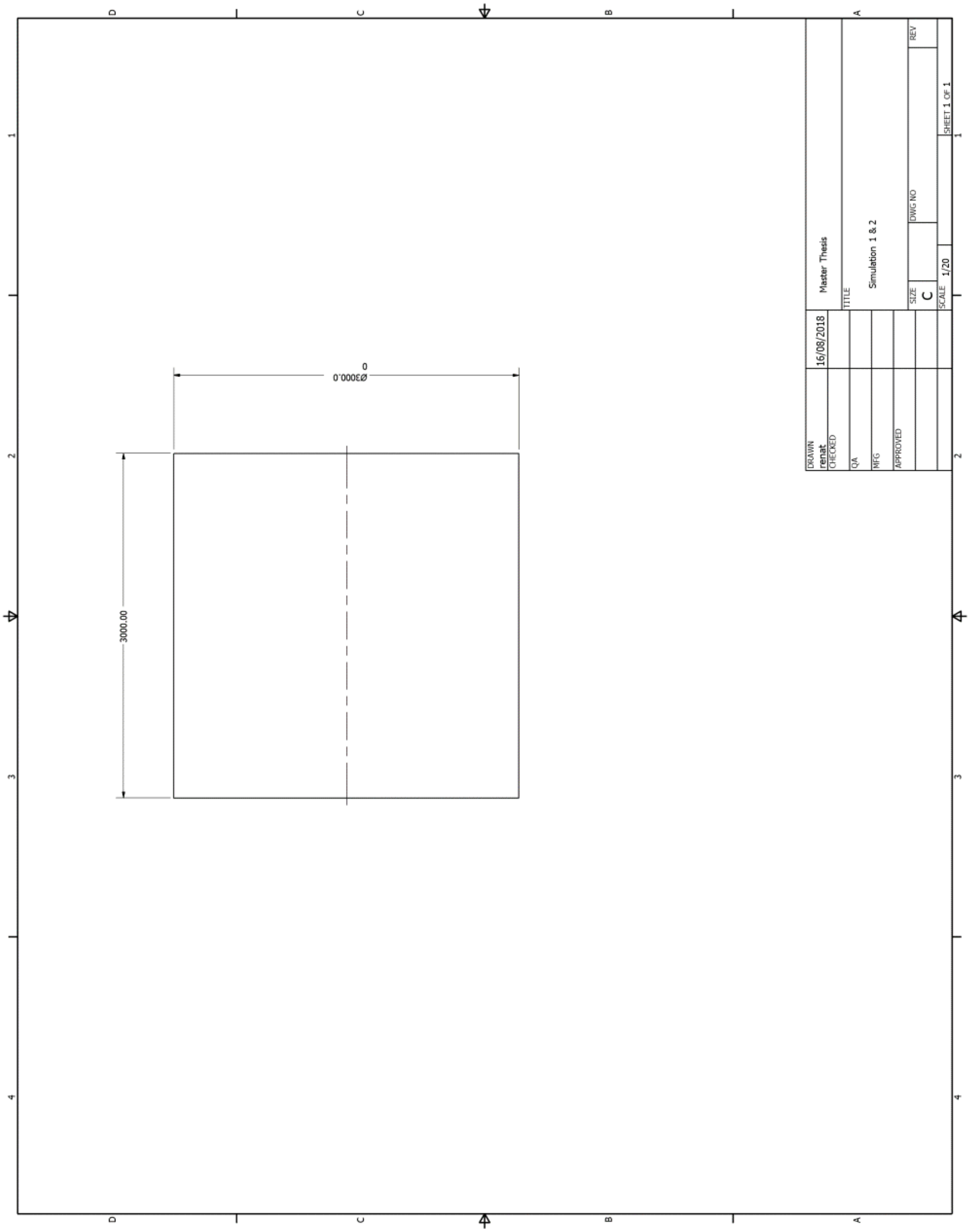
Where A is the Area of the indentation.

To calculate Vickers’s hardness H_v is calculated:

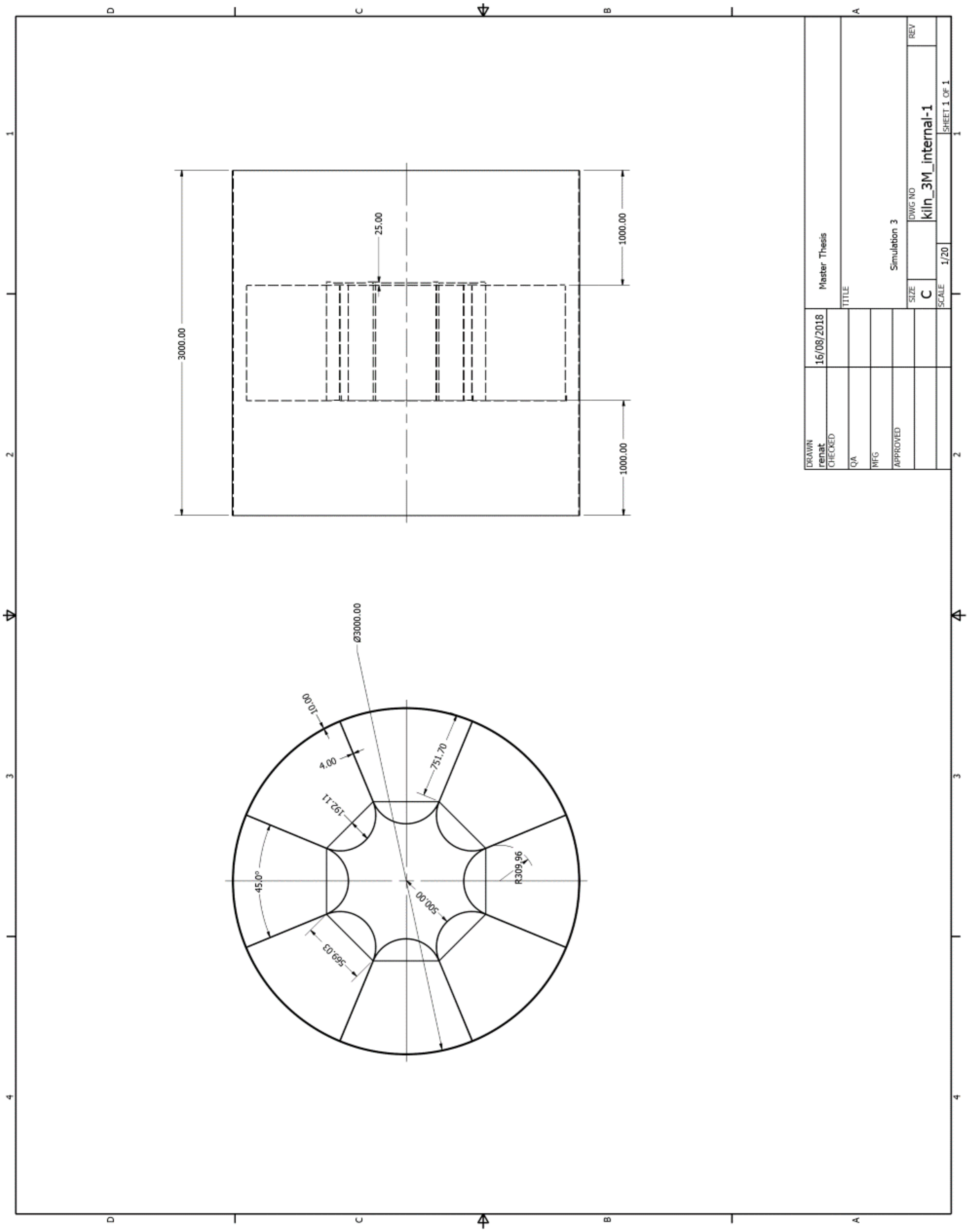
$$H_v = \frac{F}{A} \qquad \left[\frac{kg}{mm^2}\right]$$

In this test a diamond or any other hard material point with a known geometry is pressed against with material with a known force, and the resulting indentation deepness is measured.

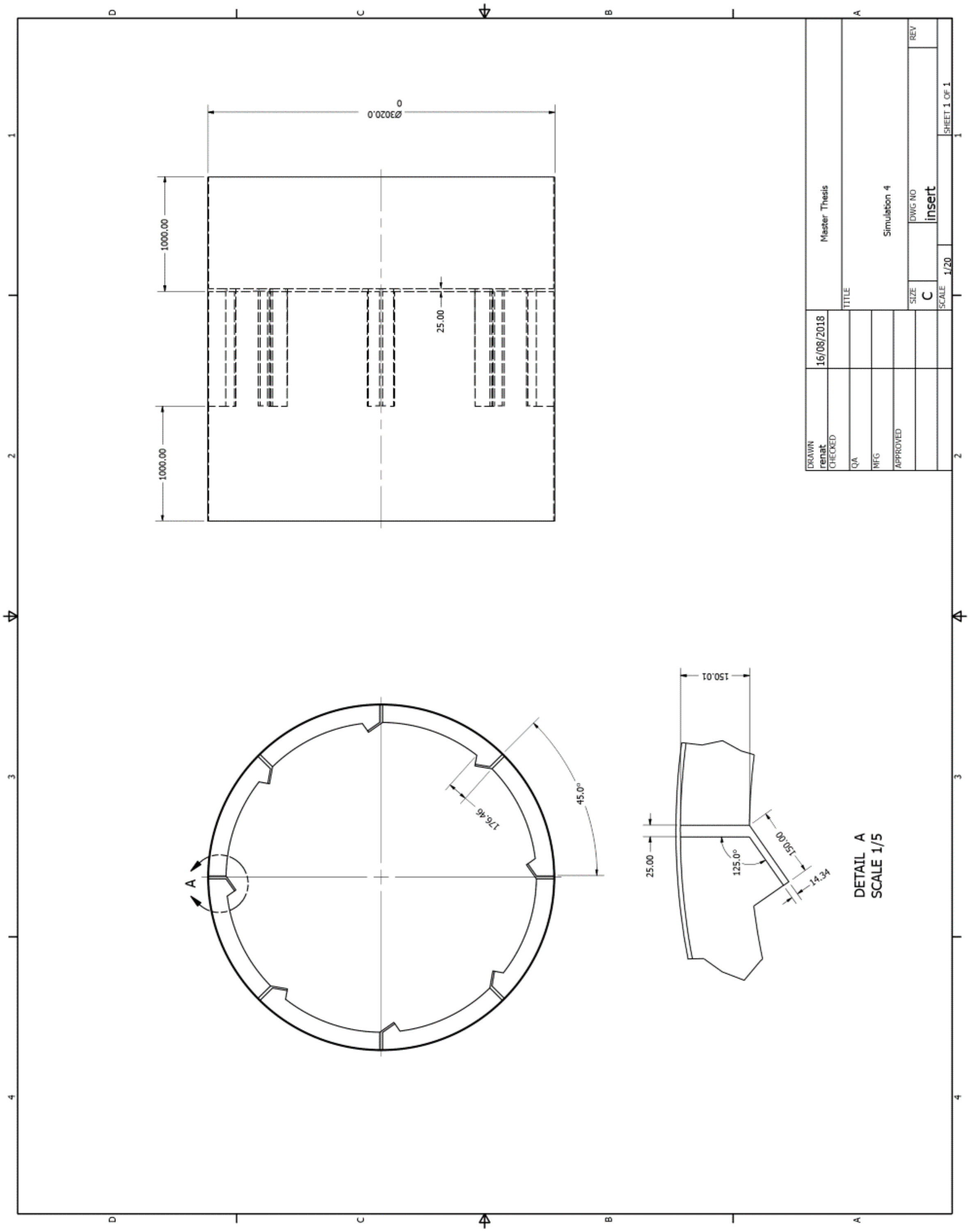
ANNEX 2 – Rotary Kiln Drawings
Simulation 1 & 2



Simulation 3



Simulation 4



ANNEX 3 – ANSYS Equations

Volume fraction

For the volume fraction calculation, the concept of phasic volume fractions is created, and it represents the actual space that each phase is taking from a given volume and that the laws of conservation of mass and momentum are fulfilled by each phase individually. The sum of these fractions is assumed to be equal to one and to be continuous functions of space and time. The formulas where retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

For Fluent the volume of phase is defined as:

$$V_q = \int_V \alpha_q \, dV$$

Where

$$\sum_{q=1}^{n} \alpha_q = 1$$

And The effective density of phase **q** , where $\boldsymbol{\rho_q}$ is the physical density of phase **q,** is

$$\hat{\rho}_q = \alpha_q \, \rho_q$$

Where

V_q is the Volume of phase q

V is the Volume

α_q is the phasic volume fraction

$\hat{\rho}_q$ is the effective density of phase **q**

$\boldsymbol{\rho_q}$ is the density of phase **q**

Conservation Equations

Conservation of mass formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

$$\frac{\delta}{\delta t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_q$$

Where

$\vec{v}_q$ is the phase velocity

$\dot{m}_{pq}$ and $\dot{m}_{qp}$ characterize the mass transfer in between the phases

S_q is the source term, on the software ANSYS is by default 0 but it can be changed

Conservation of momentum

$$\begin{aligned}\frac{\delta}{\delta t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) \\ = -\alpha_q \nabla P + \nabla \cdot \bar{\bar{\tau}}_q + \alpha_q \rho_q \vec{g} \\ + \sum_{P=1}^{n}\left(\vec{R}_{pq} + \dot{m}_{pq}\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}\right) + \left(\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{wl.q} + \vec{F}_{vm,q} + \vec{F}_{td,q}\right)\end{aligned}$$

Where $\bar{\bar{\tau}}_q$ is the stress-strain tensor of the phase q and it is defined as:

$$\bar{\bar{\tau}}_q = \alpha_q \mu_q \left(\nabla \vec{v}_q + \nabla \vec{v}_q^T\right) + \alpha_q \left(\lambda_q - \frac{2}{3}\mu_q\right) \nabla \cdot \vec{v}_q \bar{\bar{I}} \qquad (4)$$

Where

μ_q is the shear viscosity

λ_q is the bulk viscosity

$\vec{F}_q$ is the external body force

$\vec{F}_{lift,q}$ is the lift force

$\vec{F}_{wl.q}$ is the wall lubrication force

$\vec{F}_{vm,q}$ is the virtual mass force

$\vec{F}_{td,q}$ is the turbulent dispersion force, only present in the case of turbulent flow regime

$\vec{v}_{pq}$ is the interphase velocity and its value depending on the following conditions

$$\vec{v}_{pq} = \begin{cases} \vec{v}_p & \dot{m}_{pq} < 0\,;\ phase\ q\ mass\ is\ being\ transferred\ to\ phase\ p \\ \vec{v}_q & \dot{m}_{pq} > 0\,;\ phase\ p\ mass\ is\ being\ transferred\ to\ phase\ q \end{cases}$$

Conservation of energy

For the Eulerian multiphase applications each phase gets its own enthalpy equation, in order to describe the conservation of energy. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q h_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{u}_q h_q\right) = \alpha_q \frac{\delta p_q}{\delta t} + \bar{\bar{\tau}}: \nabla \vec{u}_q - \nabla \cdot \vec{q}_q + S_q + \sum_{p=1}^{n}\left(Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}\right)$$

Where

h_q is the specific enthalpy

$\vec{q}_q$ is the heat flux

S_q is the term that includes the source of enthalpy

Q_{pq} is the intensity of the heat exchange between the phases

h_{pq} is the interphase enthalpy

Additionally, the intensity of heat exchange between phases must fulfill the following conditions

$$Q_{pq} = -Q_{qp}$$

$$Q_{qq} = 0$$

Fluent Equations

The software fluent in addition to the previous mention equations uses the following set of three equations to calculate the volume fraction of each phase, fluid to fluid momentum and fluid to solid momentum. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

Volume Fraction

$$\frac{1}{\rho_{rq}}\left(\frac{\delta}{\delta t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right)=\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right)$$

Where ρ_{rq} is the reference density of the phase

Fluid-Fluid Momentum Conservation Equations

$$\begin{aligned}\frac{\delta}{\delta t}\left(\alpha_q\rho_q\vec{v}_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\vec{v}_q\right)\\ &=-\alpha_q\nabla P+\nabla\cdot\bar{\bar{\tau}}_q+\alpha_q\rho_q\vec{g}\\ &+\sum_{P=1}^{n}\left(K_{pq}\left(\vec{v}_p-\vec{v}_q\right)+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp}\right)+\left(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{wl.q}+\vec{F}_{vm,q}+\vec{F}_{td,q}\right)\end{aligned}$$

Where the variables are defined as in the general conservation of momentum

Fluid-solid Momentum Conservation Equations

$$\begin{aligned}\frac{\delta}{\delta t}\left(\alpha_s\rho_s\vec{v}_s\right)+\nabla\cdot\left(\alpha_s\rho_s\vec{v}_s\vec{v}_s\right)\\ &=-\alpha_s\nabla P-\nabla P_s+\nabla\cdot\bar{\bar{\tau}}_s+\alpha_s\rho_s\vec{g}\\ &+\sum_{l=1}^{N}\left(K_{ls}\left(\vec{v}_q-\vec{v}_s\right)+\dot{m}_{qs}\vec{v}_{qs}-\dot{m}_{sq}\vec{v}_{qs}\right)+\left(\vec{F}_s+\vec{F}_{lift,s}+\vec{F}_{vm,s}+\vec{F}_{td,s}\right)\end{aligned}$$

Where the variables are defined as in the general conservation of momentum.

To describe the Fluid-solid mixture interaction, the software ANSYS uses a granular multi-flow model, from an analogy between the thermal motion of particles in gas and the random particle motion from particle-particle collisions the solid phase stresses are derived, considering the granular phase as inelastic. To go further on this analogy, the necessary variables to determine the random gas movement are temperature and pressure but for the granular phase a variable called granular temperature are used.

For further comprehension of the conservation equations, it is necessary to define some of the coefficients, forces and variables mentioned.

Interphase Exchange Coefficients

- Fluid-Fluid Exchange Coefficient

  In the case of fluid-fluid systems, it is generally assumed that the secondary or less abundant fluid phase will generate bubbles and or droplets, for which this definition is used

$$K_{pq} = \frac{\rho_p f}{6\tau_p} d_p A_i$$

Where

A_i Is the interfacial area

f Is the drag function

τ_p Is the particle relaxation time

The particle relaxation is calculated as following

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_q}$$

- Fluid-Solid Exchange Coefficient

$$K_{sq} = \frac{\alpha_s \rho_s f}{\tau_s}$$

The particle relaxation is calculated on the following way

$$\tau_s = \frac{\rho_s d_s^2}{18\mu_q}$$

- Solid-Solid Exchange Coefficient

$$K_{qs} = \frac{3\left(1 + e_{qs}\right)\left(\frac{\pi}{2} + C_{fr,qs}\frac{\pi^2}{8}\right)\alpha_s \rho_s \alpha_q \rho_q \left(d_q + d_s\right)^2 g_{0,qs}}{2\pi\left(\rho_q d_q^3 + \rho_s d_s^3\right)}\left|\vec{v}_q - \vec{v}_s\right|$$

Where

e_{qs} is the coefficient of restitution

$C_{fr,qs}$ is the coefficient of friction between the phases

d_q and d_s are the particle diameter

$g_{0,qs}$ is the radial distribution coefficient

Turbulent Dispersion Force

The formulas where retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

$$\vec{F}_{td,q} = -\vec{F}_{td,p} = -f_{td,limiting} K_{pq} \vec{v}_{dr}$$

Where

$\vec{v}_{dr}$ is the drift velocity.

$f_{td,limiting}$ is the Limiting Functions for the Turbulent Dispersion Force.

K_{pq} is the Interphase Exchange Coefficient.

The drift velocity considers the dispersion of the phase because of turbulent fluid motion transport, on the other hand the turbulent dispersion force plays an important role on driving the secondary or turbulent phase face away from the walls and towards the center or the area located the most far from any wall.

the Limiting Functions for the Turbulent Dispersion Force is a factor that marks a limit for the turbulent dispersion force, the factor goes from 0 to 1 where 1 means that there is no limiting, finally this factor is defined on the phasic volume fraction.

$$f_{td,limiting}(\alpha_p) = \max\left(0, \min 1, \frac{\alpha_{p,2} - \alpha_p}{\alpha_{p,2} - \alpha_{p,1}}\right)$$

Where the variables are set by ANYSYS by default, but with option to change them, they are set as:

$$\alpha_{p,1} = 0.3$$

$$\alpha_{p,2} = 0.7$$

Virtual Mass Force

$$\vec{F}_{vm,q} = C_{vm}\alpha_p\rho_q\left(\frac{d_q\vec{v}_q}{dt} - \frac{d_p\vec{v}_p}{dt}\right)$$

The virtual mass force happens when the accelerating particles of the granular phase interact with the primary phase inertial forces, it can also occur when each phase has different relative acceleration. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

Lift Force

$$\vec{F}_{lift} = -C_l\rho_q\alpha_p\left(\vec{v}_q - \vec{v}_p\right) \times \left(\nabla \times \vec{v}_q\right)$$

Where

C_l is the lift coeffient

The lift force is directly proportional with the size of the particle, in other words larger particles will have a bigger impact of this force, it appears because of the velocity gradients in the flow field of the primary phase, FLUENT recements to omit this force for closely packed particles or small particles. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

Wall Lubrication Force

$$\vec{F}_{wl} = C_{wl}\rho_q\alpha_p\left|\left(\vec{v}_q - \vec{v}_p\right)_{II}\right|^2\vec{n}_w$$

Where

C_{wl} is the wall lubrication coefficient

$\left|\left(\vec{v}_q - \vec{v}_p\right)_{II}\right|$ is the relative velocity component tangential to the wall of the phase

$\vec{n}_w$ is the unit normal point away from the wall

The wall lubrication force is responsible of pushing the secondary phases away from the walls of the geometry. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

Granular Temperature

The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

$$\Theta_s = \frac{1}{3} u_{s,i} u_{s,i}$$

Where $u_{s,i}$ represents the component of the fluctuating solids velocity in the Cartesian coordinate system

For this work the model of "Gidaspow et al" is enabled in the FLUENT, in this model the diffusion coefficient for granular energy is calculated on the following way:

$$k\Theta_s = \frac{150\rho_s d_s \sqrt{\Theta\pi}}{384(1+e_{ss})g_{0,ss}}\left[1 + \frac{6}{5}\alpha_s g_{0,ss}(1+e_s)\right]^2 + 2\rho_s \alpha_s^2 d_s (1+e_{ss}) g_{0,ss}\sqrt{\frac{\Theta_s}{\pi}}$$

The collisional dissipation of energy in this work is deffined as for the Lun et al model, and represents the energy disipation due to collitions

$$\gamma_{\Theta m} = \frac{12(1-e_{ss}^2)g_{0,ss}}{d_s\sqrt{\pi}}\rho_s \alpha_s^2 \Theta_s^{\frac{3}{2}}$$

The transfer of the kinetic energy of random fluctuations in particle velocity between phases is defined as:

$$\phi_{ls} = -3K_{ls}\Theta_s$$

The shear force for a granular phase at the wall will be obtain from

$$\vec{\tau}_s = -\frac{\pi}{6}\sqrt{3}\phi\frac{\alpha_s}{\alpha_{s,max}}\rho_s g_0\sqrt{\Theta_s}\vec{U}_{s,L}$$

Where

$\vec{U}_{s,L}$ is the slip velocity parallel to the wall of the particle

ϕ is the specularity coefficient between particle and wall

$\alpha_{s,max}$ is the volume fraction at maximum packing level

And finally:

$$q_s = \frac{\pi}{6}\sqrt{3}\phi\frac{\alpha_s}{\alpha_{s,max}}\rho_s g_0\sqrt{\Theta_s}\vec{U}_{s,L}\cdot\vec{U}_{s,L} - \frac{\pi}{4}\sqrt{3}\frac{\alpha_s}{\alpha_{s,max}}(1-e_{sw}^2)\rho_s g_0\Theta_s^{\frac{3}{2}}$$

To define a granular phase, it is necessary to consider the following calculations as well

Solid Shear Stress

The solids stress tensor is made from the shear and viscosities happening from particle momentum exchange due to translation and collision. The formulas were retrieved from the ANSYS FLUENT 12.0 Theory Guide. [1]

$$\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr}$$

The solid shear stress is composed of the collisional viscosity, kinetic viscosity and bulk viscosity

- Collisional Viscosity

$$\mu_{s,col} = \frac{4}{5}\alpha_s\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{\frac{1}{2}}\alpha_s$$

- Kinetic Viscosity

In the case of this work, the Gidaspow model for kinetic viscosity was chosen.

$$\mu_{s,kin} = \frac{10\rho_s d_s\sqrt{\Theta_s\pi}}{96\alpha_s(1+e_{ss})g_{0,ss}}\left[1+\frac{5}{4}g_{0,ss}\alpha_s(1+e_{ss})\right]^2\alpha_s$$

- Bulk Viscosity

In the case of this work, the Lun et al model for Bulk Viscosity was chosen.

$$\lambda_s = \frac{4}{3}\alpha_s^2\rho_s d_s g_{0,ss}(1+e_{ss})\left(\frac{\Theta_s}{\pi}\right)^{\frac{1}{2}}$$

Bulk viscosity describes the resistance of the group of granular particles to compression and expansion

- Frictional Viscosity

In the case of this work, the Schaeffer’s model for Frictional Viscosity was chosen.

$$\mu_{s,fr} = \frac{p_s\sin\phi}{2\sqrt{I_{2D}}}$$

Where

p_s is the solid pressure

ϕ is the angle of internal friction

I_{2D} is the second invariant of the deviatoric stress tensor

- frictional pressure

$$P_{friction} = Fr\frac{\left(\alpha_s - \alpha_{s,min}\right)^n}{\left(\alpha_{a,min} - \alpha_s\right)^p}$$

Where Fr is defined as

$$Fr = 0.1\alpha_s$$

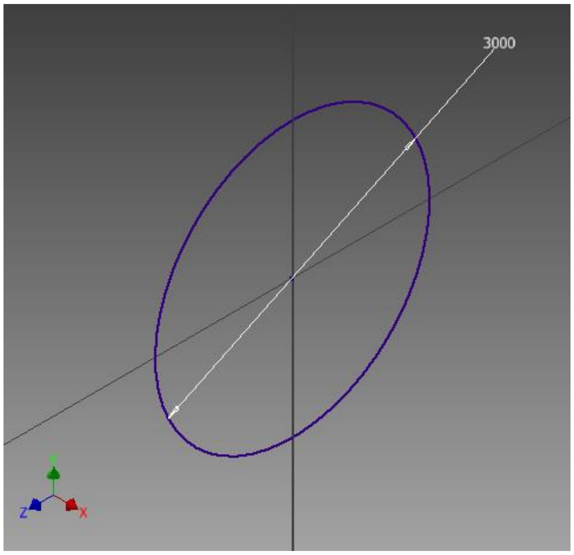
ANNEX 4 Simulation Method

Simulation 1

For the first simulation, as mention before, the surface of the wall was smooth, and the rotation of the system was achieved with the moving wall option, in other words the mesh was fix. The full simulation process is the next one:

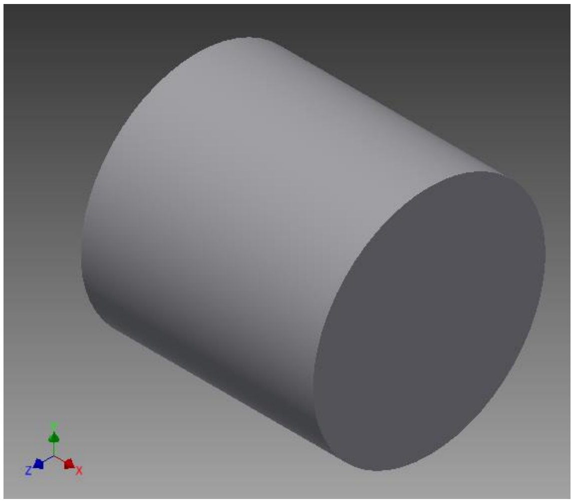
3D Drawing

First using the software Inventor professional 2015 with academic license, a cylinder with 3 meters of diameter was stablish with center on origin of x,y and z and using the y-z plane. As show on the figure 40



Simulation 1 kiln diameter

Then the figure was extruded along the x axis for 3 meters to complete the smooth segment of the kiln



Simulation 1 kiln Extrusion

The resulting body was saved on Step format (*.stp). For then been open on the Ansys 16.2 software on the geometry tool as shown in the figure 42

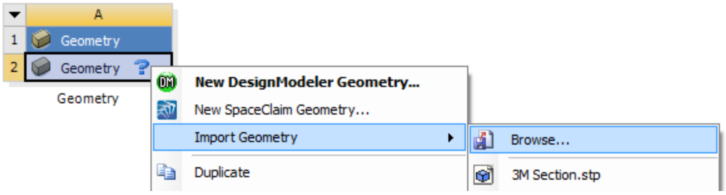
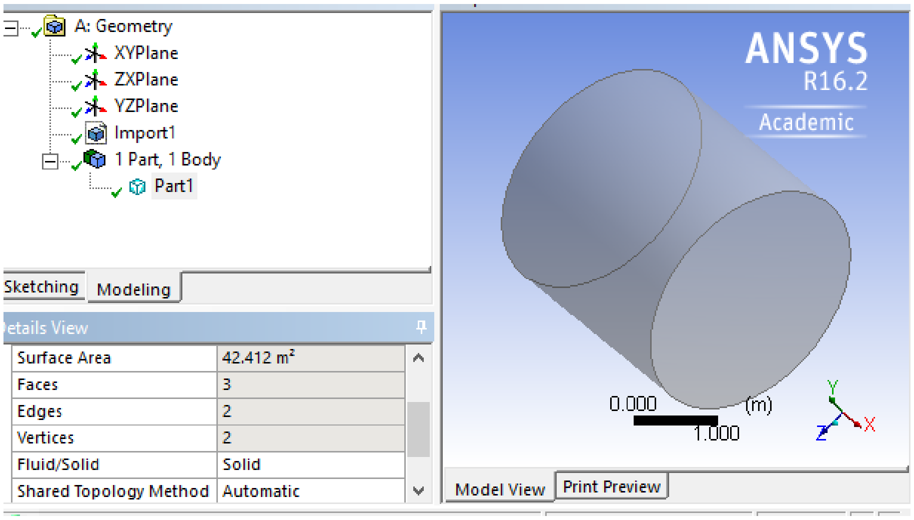


Figure 42; Simulation 1 Geometry Exporting

Once the file is load, it was opened on the geometry tool, where the part was changed from solid to fluid, on the details of body menu as shown on the figure 43.



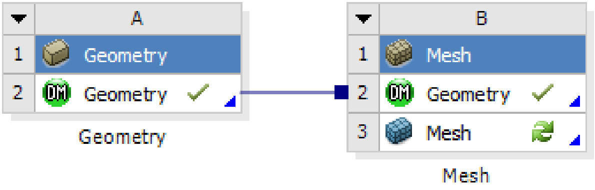
Surface Area	42.412 m²
Faces	3
Edges	2
Vertices	2
Fluid/Solid	Solid
Shared Topology Method	Automatic

; Simulation 1 Solid/Fluid

Then on the surface named inlet a new sketch was created, here a new circle was placed almost on the bottom of the inlet, to simulate the inlet of the granular flow. The circle had a diameter of 0.25m

Mesh

Then the Meshing tool was called into the project schematics as the following step.

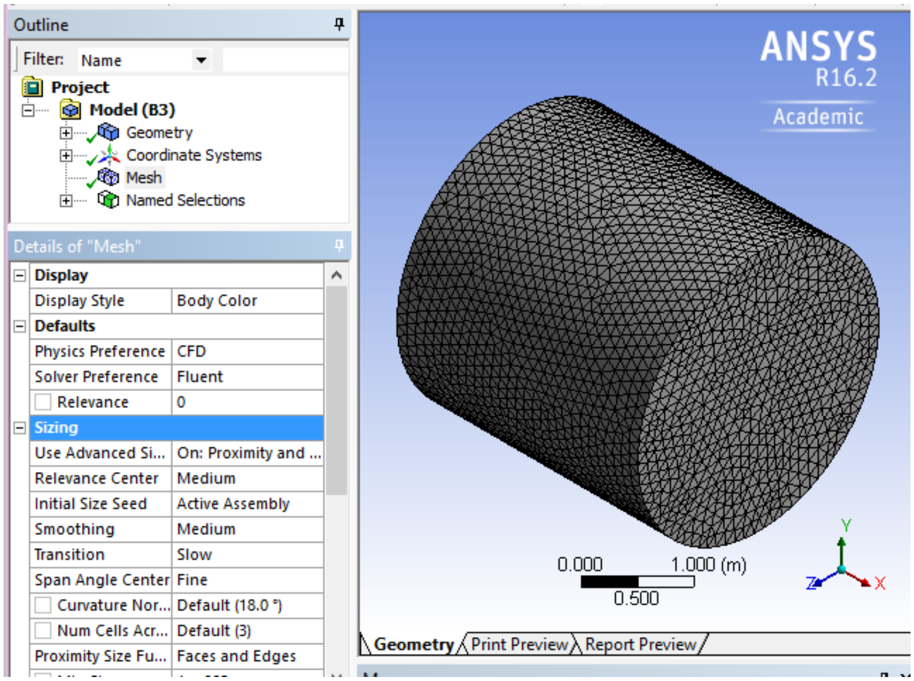


Simulation 1 Project Bench

The mesh was generated changing the following options on the details of mesh menu:

1.- Physical References: CFD
2.- Solver Preferences: Fluent
3.- Use advance Size Function: on: Proximity and curvature
4.- Relevance Center: Fine
5.- Smoothing: High

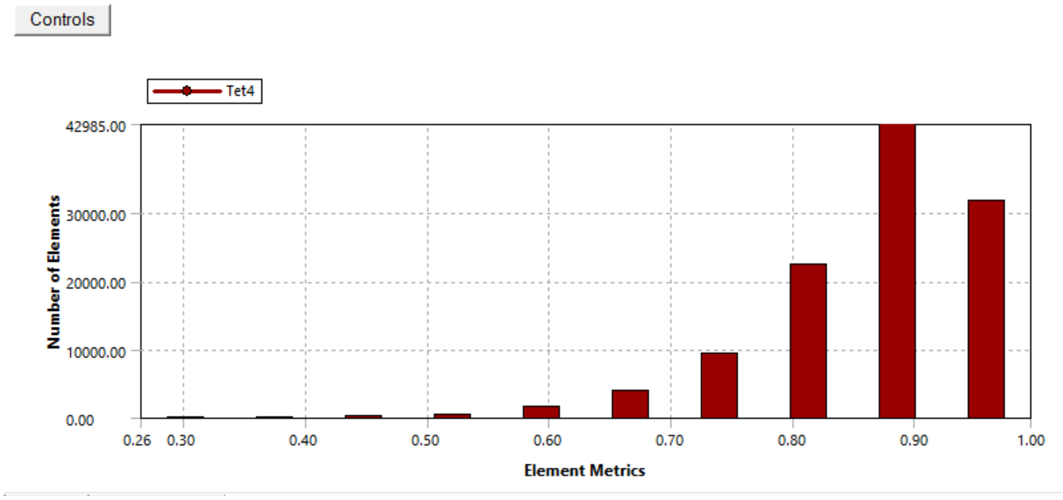
The rest of the option where left on default settings, the generated mesh is shown in the next figure ****



Display	
Display Style	Body Color
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
☐ Relevance	0
Sizing	
Use Advanced Si...	On: Proximity and ...
Relevance Center	Medium
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Slow
Span Angle Center	Fine
☐ Curvature Nor...	Default (18.0 °)
☐ Num Cells Acr...	Default (3)
Proximity Size Fu...	Faces and Edges

Simulation 1 Meshing

This mesh has the following orthogonal quality values, shown on the next figure 45:

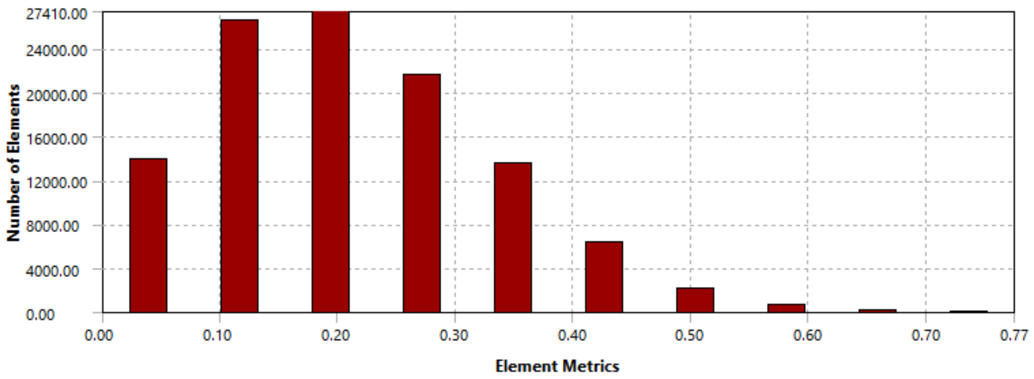


Simulation 1 Orthogonal Quality

- Nodes: 20,684
- Elements: 112,275

- Mesh metrics, orthogonal quality:
- Min 0.26432
- Max: 0.99507
- Average 0.8655
- Standard Deviation: 8.39874e-002

And a under the skewness measurement, as shown on the next figure:

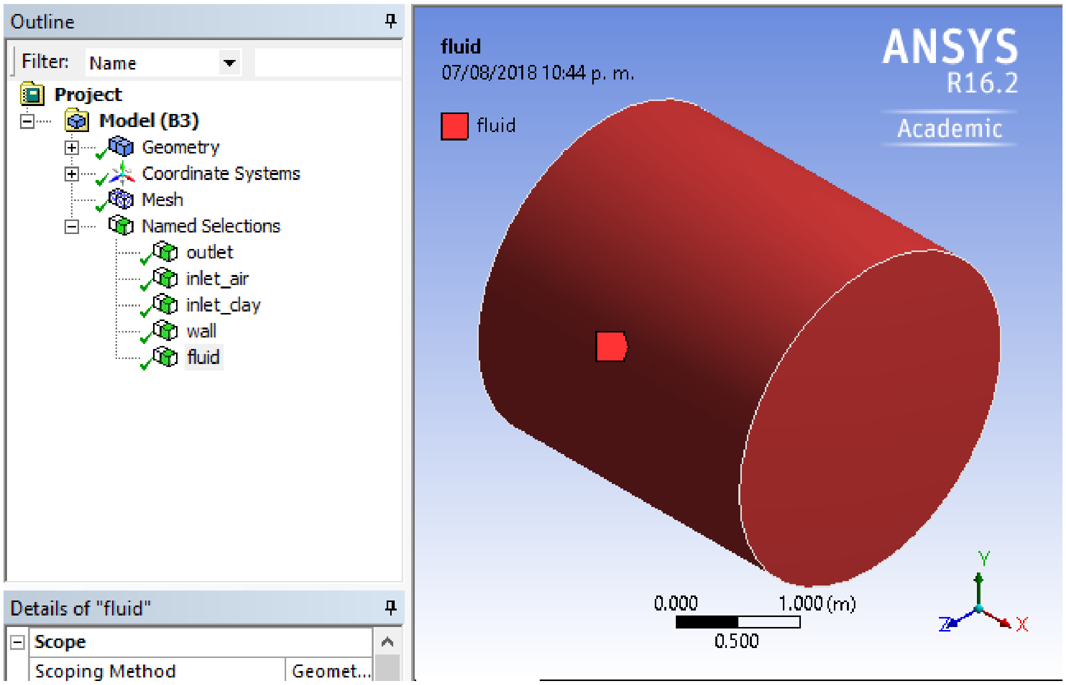


; Simulation 1 Skewness

- Min: 5.952e-006
- Max: 0.77462
- Average: 0.2113
- Standard Deviation: 0.1168

Then the named sections are created, in this case:

- Inlet_Clay
- Inlet_Air
- Outlet
- Wall
- Fluid



Outline

Filter: Name

- Project
  - Model (B3)
    - Geometry
    - Coordinate Systems
    - Mesh
    - Named Selections
      - outlet
      - inlet_air
      - inlet_day
      - wall
      - fluid

Details of "fluid"

Scope

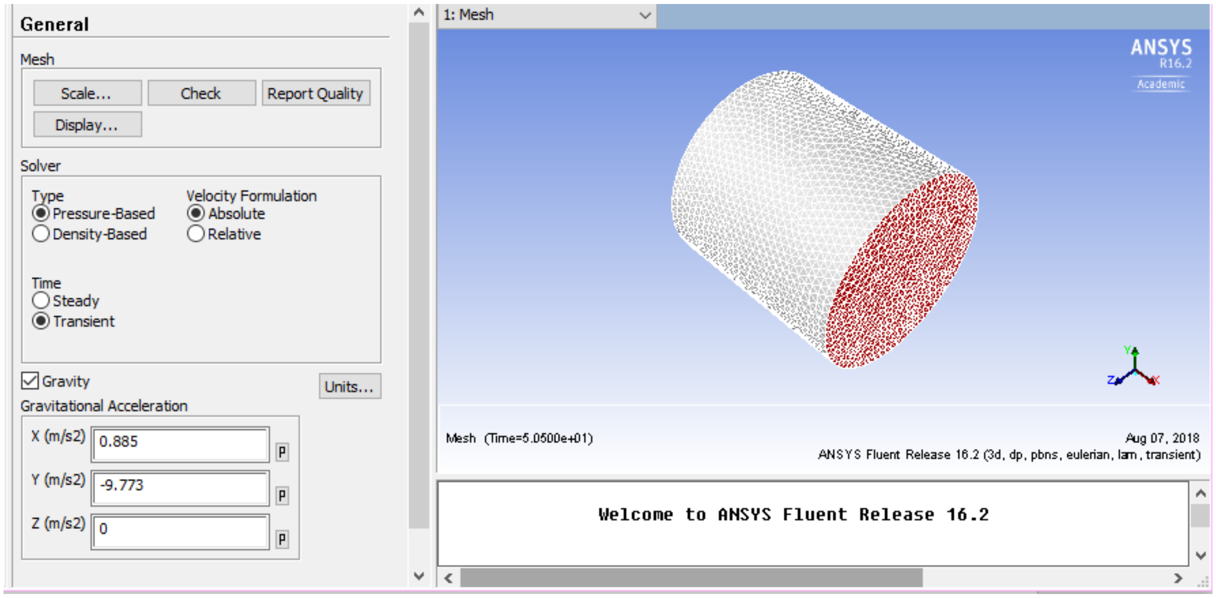
Scoping Method: Geomet...

: Simulation 1 Named Sections

The previous figure shows the named sections, more specifically the fluid one. Once the mesh is done it is exported using the Fluent import File format (*.msh).

Fluent

The mesh file is imported to fluent where the settings where done as shown the next sequence.



General

Mesh

Solver

Type: ● Pressure-Based ○ Density-Based

Velocity Formulation: ● Absolute ○ Relative

Time: ○ Steady ● Transient

☑ Gravity

Gravitational Acceleration

X (m/s2): 0.885

Y (m/s2): -9.773

Z (m/s2): 0

Mesh (Time=5.0500e+01)

Aug 07, 2018

ANSYS Fluent Release 16.2 (3d, dp, pbns, eulerian, lam, transient)

```
Welcome to ANSYS Fluent Release 16.2
```

Simulation 1 General Menu Fluent

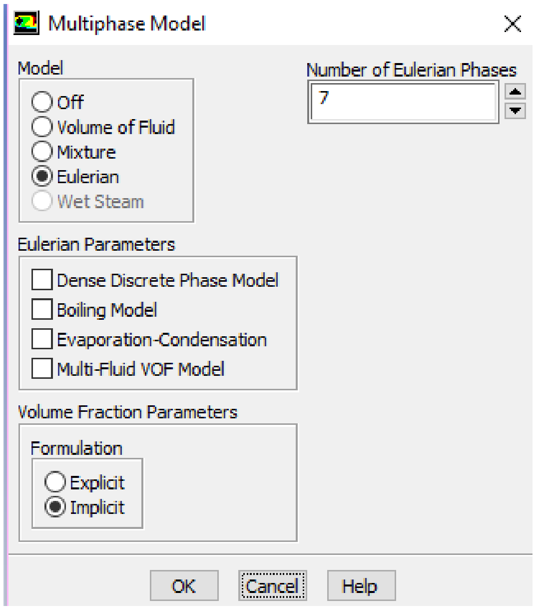
-General

- Type: Pressure-Based
- Time: Transient
- Gravity: on
- X: 0.885
- Y: -9.773

The gravity components where calculated previously, considering the inclination of the kiln.

-Models

- Multiphase: Eulerian
  - Formulation: Implicit
  - Number of Eulerian Phases: 7, as shown on the next figure 50:



Multiphase Model

Model
○ Off
○ Volume of Fluid
○ Mixture
● Eulerian
○ Wet Steam

Number of Eulerian Phases
7

Eulerian Parameters
☐ Dense Discrete Phase Model
☐ Boiling Model
☐ Evaporation-Condensation
☐ Multi-Fluid VOF Model

Volume Fraction Parameters
Formulation
○ Explicit
● Implicit

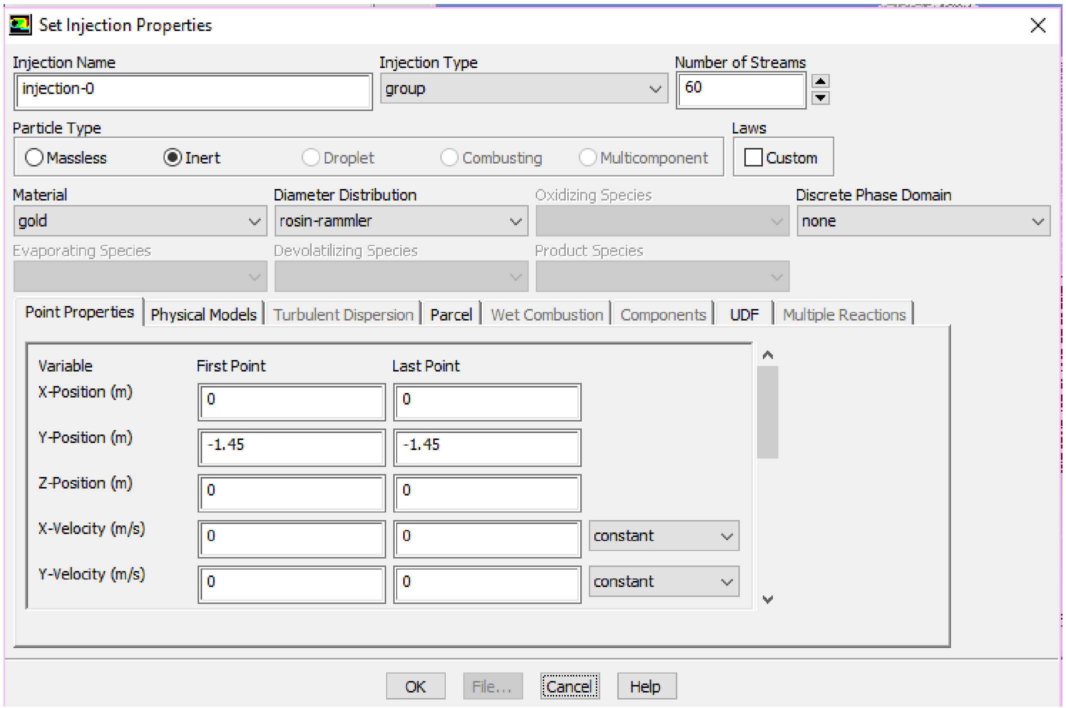
: Simulation 1 Multiphase menu.

7 phases where used, one to represent the hot gat, and the rest for the particles, where each phase represents a particle diameter ranging from 2 to 12 mm, with increments of 2 mm in between them

- Discrete Phase: on
  - Interaction with continuous flow: on
  - Update DPM sources Every Flow Iteration
  - Number of Continues phase iterations per DPM iteration: 10
  - Unsteady particle tracking: on
  - Track with fluid time step: on
  - Max number of Steps: 500
  - Step length factor: 5
  - Parallel – Methods – Hybrid

- Injections
    - Number of streams: 60
    - Particle type: Inert
    - Material: Gold
    - Diameter Distribution: Rosin-Rammler
    - Discrete phase Demine: None
    - First X-Position (m): 0
    - Last X-Position (m): 0
    - First Y-Position (m): -1.45
    - Last Y-Position (m): -1.45
    - Start Time (s): 0
    - Stop Time (s): 10000
    - Flow Rate: (kg/s): 0.07
    - Min. Diameter (m): 0.002
    - Max. Diameter (m): 0.012
    - Mean. Diameter (m): 0.006
    - Spread Parameter: 3.5 (Default)

The injections are the way the software ANSYS call the introduction of the discrete phase particles to the system. The setting menu for them of show on the next figure:



Set Injection Properties

Injection Name: injection-0
Injection Type: group
Number of Streams: 60
Particle Type: ○ Massless ● Inert ○ Droplet ○ Combusting ○ Multicomponent
Laws: ☐ Custom
Material: gold
Diameter Distribution: rosin-rammler
Oxidizing Species
Discrete Phase Domain: none
Evaporating Species
Devolatilizing Species
Product Species

Variable	First Point	Last Point	
X-Position (m)	0	0	
Y-Position (m)	-1.45	-1.45	
Z-Position (m)	0	0	
X-Velocity (m/s)	0	0	constant
Y-Velocity (m/s)	0	0	constant

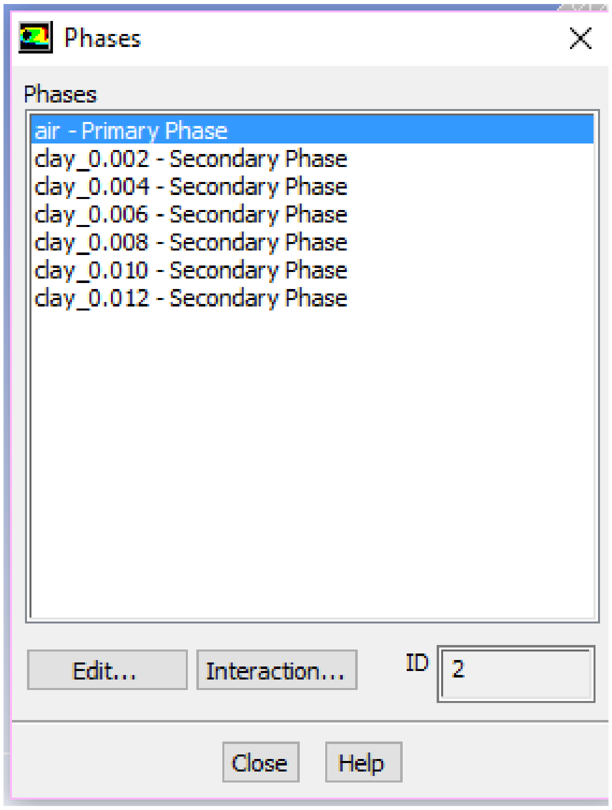
Simulation 1 Injections

- Materials
    - Fluid
        - Silicon-Solid

            - Density: 1760 kg/m3
        - Air
    - Solid
        - Aluminum
    - Inter Particle
        - Gold
            - Density: 1760 kg/m3
- Phases
    - Air – Primary Phase
        - Air
    - Clay_0.002 – Secondary Phase
        - Silicon Solid
            - Granular
            - Granular temperature Model: Phase Property
            - Diameter (m): 0.002
            - Granular Viscosity: Gidaspow
            - Granular Bulk Viscosity: Constant
            - Frictional Viscosity: Johnson-et-al
            - Angle of internal Friction: 30.0007
            - Frictional Pressure: Based-KTGF
            - Frictional modulus: Derived
            - Friction Packing Limit: 0.61
            - Granular Temperature: Algebraic
            - Solids Pressure: Lun-et-al
            - Radial Distribution: Lun-et-al
            - Elastic Modules Derived
            - PAcking Limit: 0.63
    - Clay_0.004 – Secondary Phase
        - Same settins except
            - Diameter (m): 0.004
    - Clay_0.006 – Secondary Phase
        - Same settins except
            - Diameter (m): 0.006
    - Clay_0.008 – Secondary Phase
        - Same settins except
            - Diameter (m): 0.008
    - Clay_0.010 – Secondary Phase
        - Same settins except
            - Diameter (m): 0.010
    - Clay_0.012 – Secondary Phase
        - Same settins except
            - Diameter (m): 0.012

- Interactions
  - Collisions: All possible variables: 0.5

As shown on the Figure XXX, the air phase is considered as primary phase.



Phases

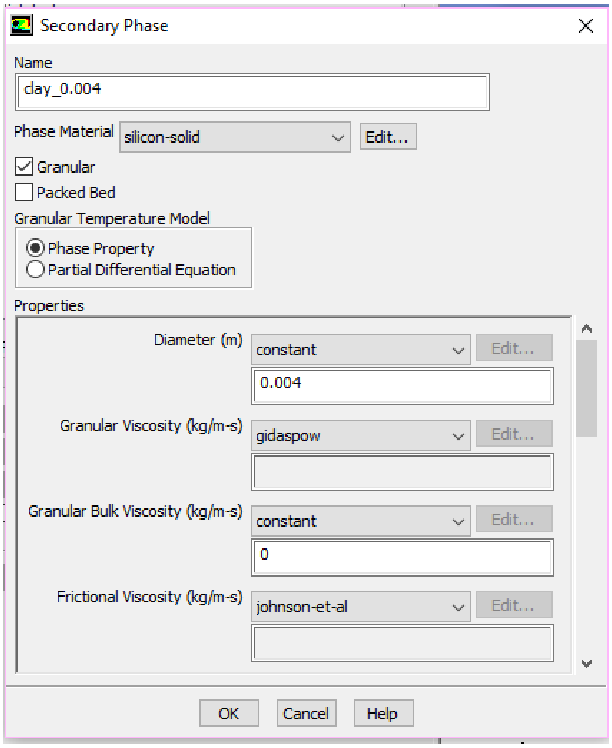
Phases

air - Primary Phase
clay_0.002 - Secondary Phase
clay_0.004 - Secondary Phase
clay_0.006 - Secondary Phase
clay_0.008 - Secondary Phase
clay_0.010 - Secondary Phase
clay_0.012 - Secondary Phase

ID 2

Simulation 1 Phases

For all the Clay phases, secondary phases, the material has to be selected as well as the properties of it, as shown on the next figure.



Name: clay_0.004

Phase Material: silicon-solid

☑ Granular

☐ Packed Bed

Granular Temperature Model

● Phase Property

○ Partial Differential Equation

Properties

Diameter (m): constant, 0.004

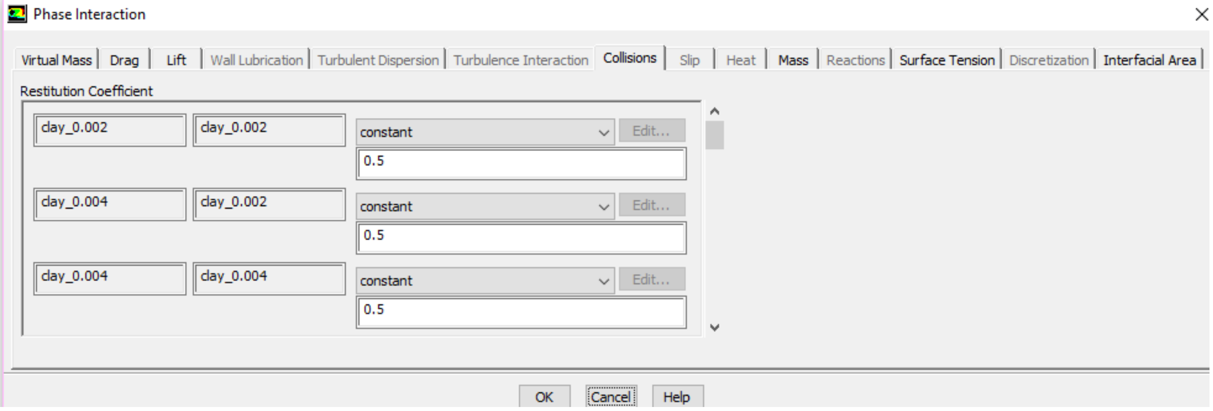
Granular Viscosity (kg/m-s): gidaspow

Granular Bulk Viscosity (kg/m-s): constant, 0

Frictional Viscosity (kg/m-s): johnson-et-al

: Simulation 1 Secondary Phases

The restitution coefficient has to be specified for all the permutations of secondary phases



Restitution Coefficient

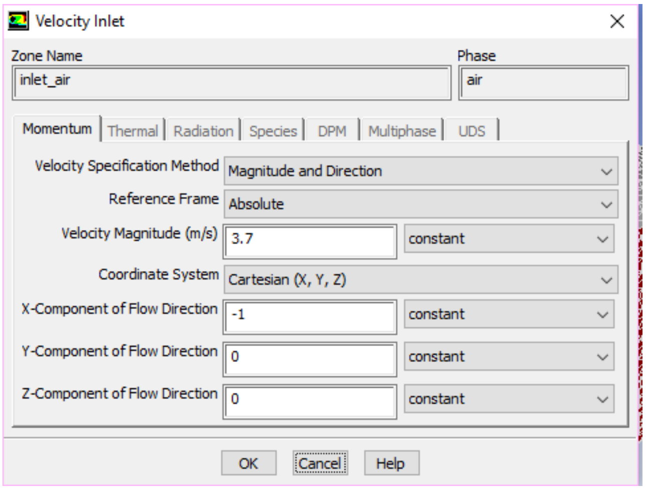
clay_0.002	clay_0.002	constant	0.5
clay_0.004	clay_0.002	constant	0.5
clay_0.004	clay_0.004	constant	0.5

: Simulation 1 Collisions

- Boundary Conditions
  - Inlet Air: Phase Air
    - Velocity Specification Method: Magnitude and Direction
    - Velocity magnitude (m/s) 3.7
    - X-Component of Flow direction: -1
    - Y-Component of Flow direction: 0
    - Z-Component of Flow direction: 0

- Inlet Clay: Phases: Clay_0.002, Clay_0.004, Clay_0.006, Clay_0.008, Clay_0.010, Clay_0.012.
    - Velocity Specification Method: Magnitude and Direction
    - Velocity magnitude (m/s) 0.07
    - X-Component of Flow direction: -1
    - Y-Component of Flow direction: 0
    - Z-Component of Flow direction: 0
    - Granular Temperature: 0.0001
    - Multiphase: Volume Fraction: 0.166
      *the same for all the Clay Phases
- Wall: Phase Mixture
    - Momentum: Moving Wall
    - Motion: Relative to adjacent cell
    - Rotational
    - Speed: 5 RPM
    - Rotation-Axis Direction:
        - X:1
        - Y:0
        - Z:0
    - DPM
        - Boundary Condition Type: Reflect
        - Discrete Phase Reflection Coefficient: Normal 0.83
        - Discrete Phase Reflection Coefficient: Tangential 0.83

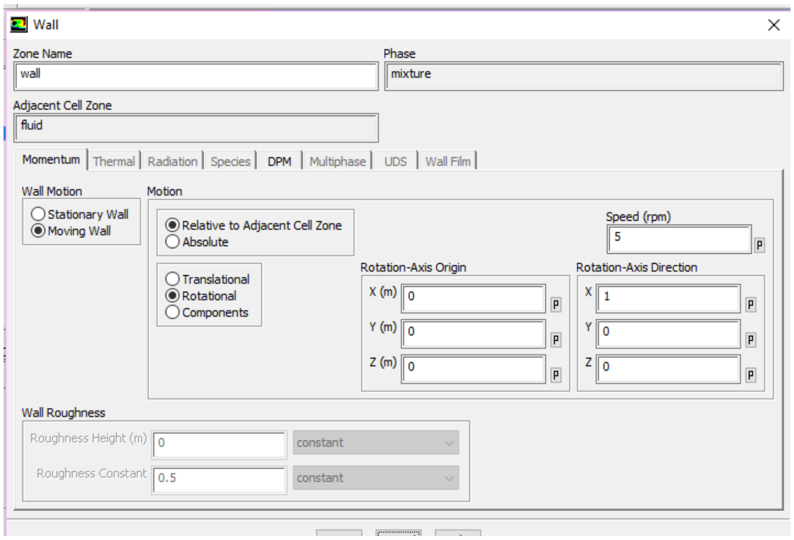
On the boundary condition menu, for the inlet air, the velocity and direction of the air as well as its multiphase ratio, if necessary, can be specified as shown on the next figure 54.



Zone Name: inlet_air
Phase: air
Velocity Specification Method: Magnitude and Direction
Reference Frame: Absolute
Velocity Magnitude (m/s): 3.7 constant
Coordinate System: Cartesian (X, Y, Z)
X-Component of Flow Direction: -1 constant
Y-Component of Flow Direction: 0 constant
Z-Component of Flow Direction: 0 constant

Simulation 1 Boundary Conditions Air

On the boundary condition menu, for the wall, the velocity and direction of the rotation can be specified, where the value of -1 or 1 will indicate the clock or anti clock wise rotation, as shown on the next figure 55:

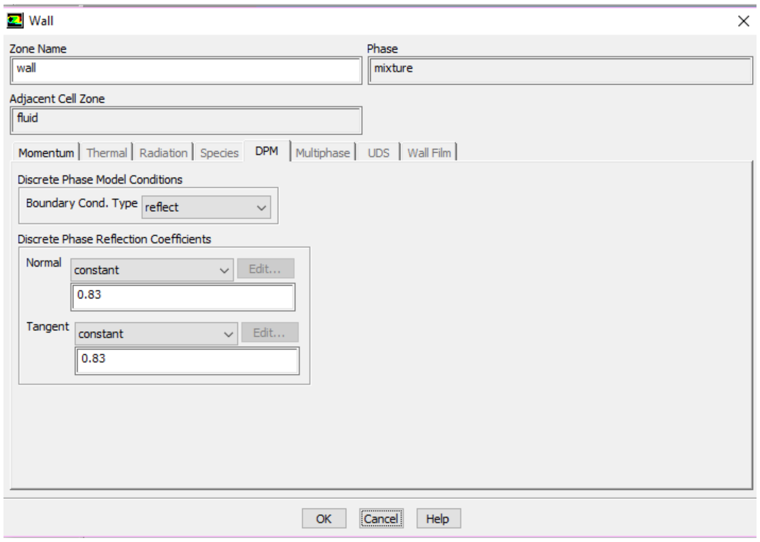


Zone Name: wall
Phase: mixture
Adjacent Cell Zone: fluid

Wall Motion: ○ Stationary Wall ● Moving Wall
Motion: ● Relative to Adjacent Cell Zone ○ Absolute
○ Translational ● Rotational ○ Components
Speed (rpm): 5
Rotation-Axis Origin: X (m) 0, Y (m) 0, Z (m) 0
Rotation-Axis Direction: X 1, Y 0, Z 0
Wall Roughness
Roughness Height (m): 0 constant
Roughness Constant: 0.5 constant

Simulation 1 Moving Wall

The values of the DPM menu for, Discrete phase Reflection Coefficient are very important because they will determine the behavior of the particles, they can be set as shown on the nest figure.

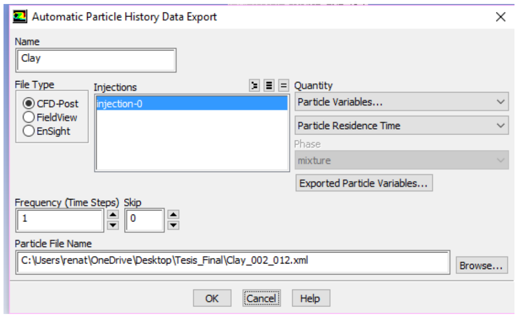


Zone Name: wall
Phase: mixture
Adjacent Cell Zone: fluid

Discrete Phase Model Conditions
Boundary Cond. Type: reflect
Discrete Phase Reflection Coefficients
Normal: constant 0.83
Tangent: constant 0.83

Simulation 1 DPM coefficients

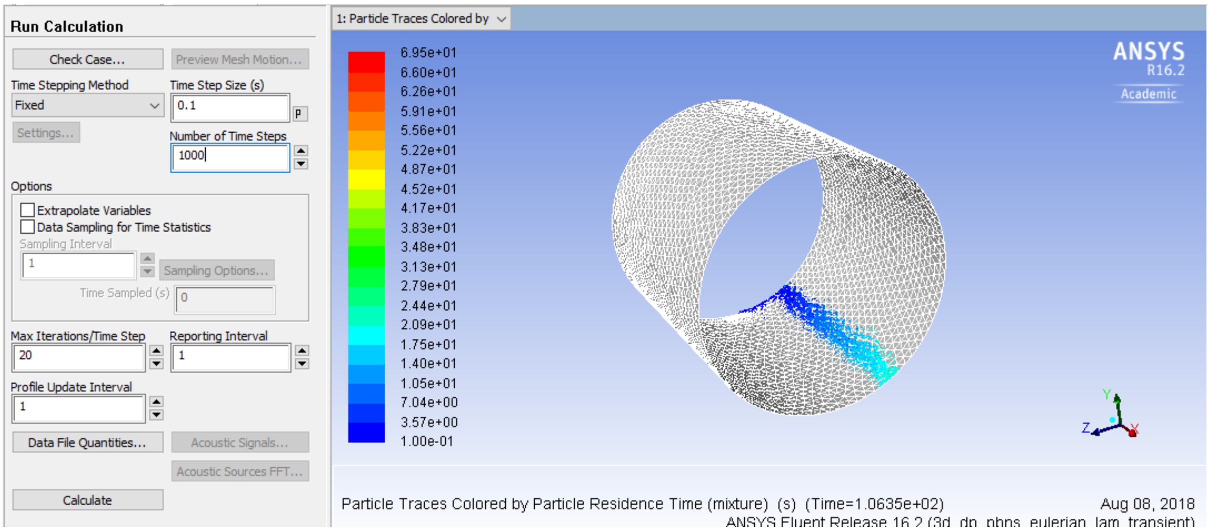
An Automatic Particle Export Data file was created, saving the Residence time of the particles, diameter and position among the X axis. As Shown on the figure



Name: Clay
File Type: ● CFD-Post ○ FieldView ○ EnSight
Injections: injection-0
Quantity: Particle Variables...
Particle Residence Time
Phase: mixture
Frequency (Time Steps): 1
Skip: 0
Particle File Name: C:\Users\renat\OneDrive\Desktop\Tesis_Final\Clay_002_012.xml

Simulation 1 Particle File

The simulation was Run for 100 seconds with a time step of 0.1 Seconds and 20 interactions per time step. As shown on the next figure



Time Stepping Method: Fixed
Time Step Size (s): 0.1
Number of Time Steps: 1000
☐ Extrapolate Variables
☐ Data Sampling for Time Statistics
Sampling Interval: 1
Time Sampled (s): 0
Max Iterations/Time Step: 20
Reporting Interval: 1
Profile Update Interval: 1

Particle Traces Colored by Particle Residence Time (mixture) (s) (Time=1.0635e+02) Aug 08, 2018
ANSYS Fluent Release 16.2 (3d dp pbns eulerian lam transient)

Simulation 1 Time Step

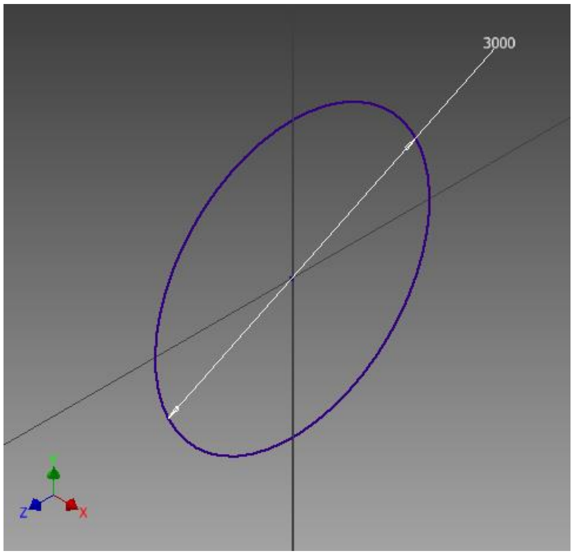
Simulation 2

Simulation 4

For the first simulation, as mention before- The internal construction of the real kiln will be simulated, and the rotation of the system was achieved with the moving frame option, in other words, the mesh is moving. The full simulation process is the next one:

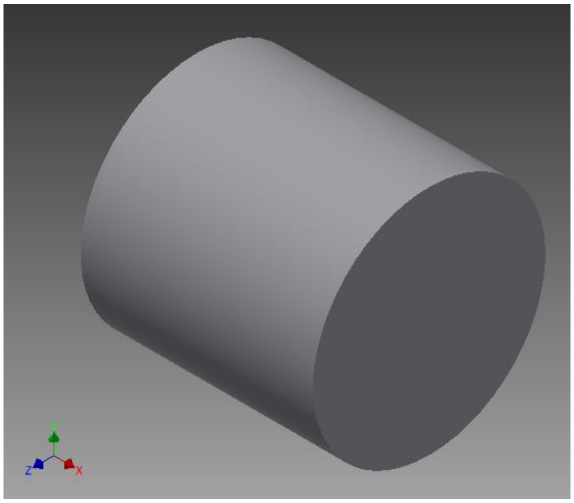
3D Drawing

First using the software Inventor professional 2015 with academic license, a cylinder with 3 meters of diameter was stablish with center on origin of x,y and z and using the y-z plane. As shown on the figure 89.



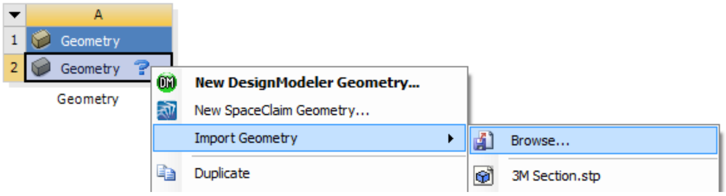
Simulation4 Kiln Extrusion

Then the figure was extruded along the x axis for 3 meters to complete the smooth segment of the kiln



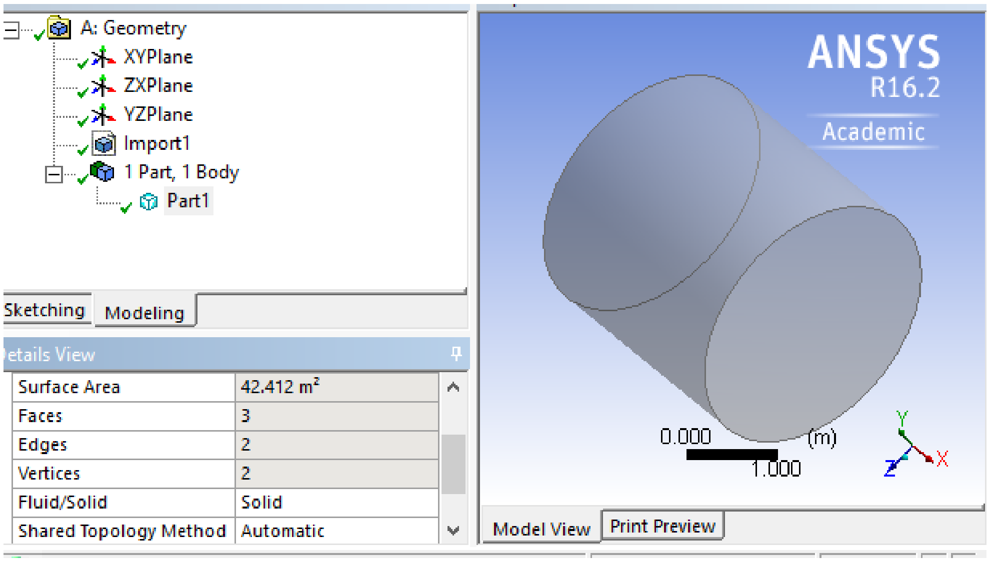
Simulation 4 Kiln Internal shape

The resulting body was saved on Step format (*.stp). For then been open on the Ansys 16.2 software on the geometry tool as shown in the figure 91



Simulation4 Geometry Exporting

Once the file is load, it was opened on the geometry tool, where the part was changed from solid to fluid, on the details of body menu as shown on the picture

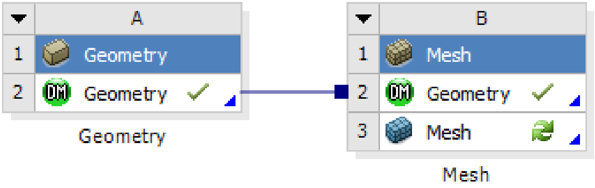


Surface Area	42.412 m^2
Faces	3
Edges	2
Vertices	2
Fluid/Solid	Solid
Shared Topology Method	Automatic

Simulation4 Solid/Fluid

Mesh

Then the Meshing tool was called to into the project schematics as the following step.

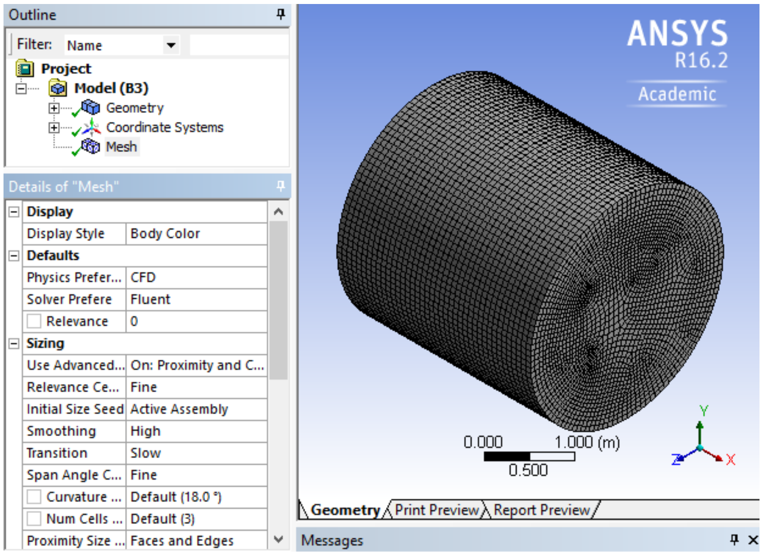


Simulation4 Project Bench

The mesh was generated changing the following options on the details of mesh menu:

1.- Physical References: CFD
2.- Solver Preferences: Fluent
3.- Use advance Size Function: on: Proximity and curvature
4.- Relevance Center: Fine
5.- Smoothing: High

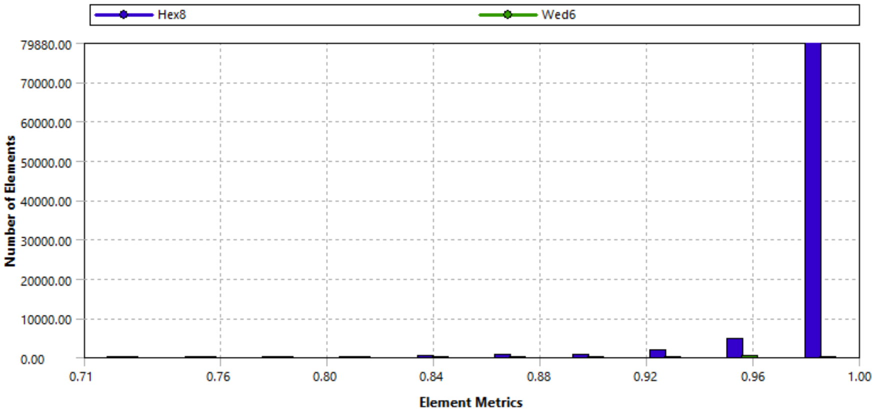
The rest of the option where left on default settings, the generated mesh is shown in the next figure 94.



Display	
Display Style	Body Color
Defaults	
Physics Prefer...	CFD
Solver Prefere	Fluent
☐ Relevance	0
Sizing	
Use Advanced...	On: Proximity and C...
Relevance Ce...	Fine
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Slow
Span Angle C...	Fine
☐ Curvature ...	Default (18.0 °)
☐ Num Cells ...	Default (3)
Proximity Size ...	Faces and Edges

Simulation4 Meshing

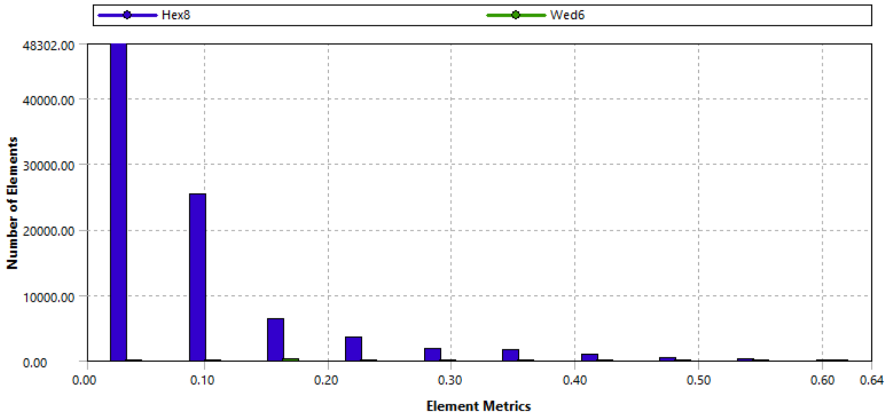
This mesh has the following orthogonal quality values, shown on the next figure:



Simulation4 Orthogonal Quality

- Nodes: 92,742
- Elements: 88,120
- Mesh metrics, orthogonal quality:
- Min 0.70895
- Max: 0.9999
- Average 0.9891
- Standard Deviation: 2.2534e-002

And a under the skewedness measurement, as shown on the next figure:

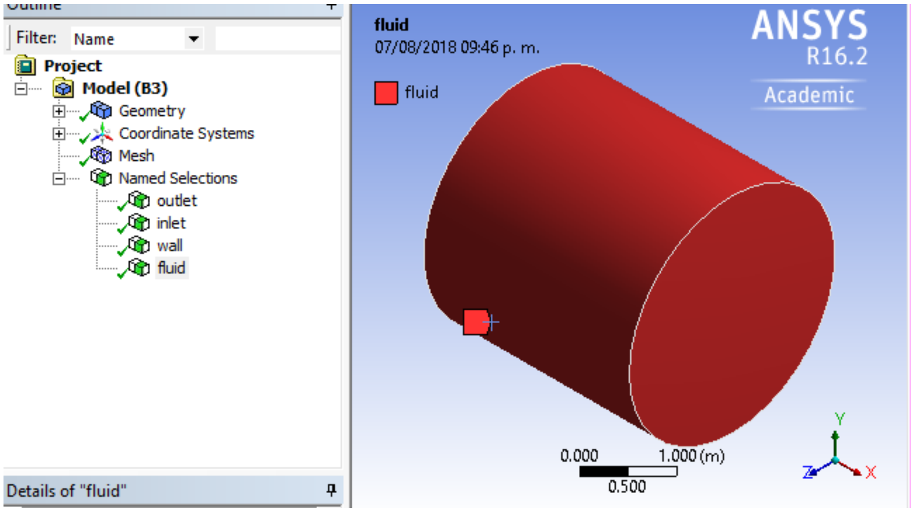


Simulation4 Skewness

- Min: 4.8263e-003
- Max: 0.63981
- Average: 8.8145e-002
- Standard Deviation: 8.0409e-002

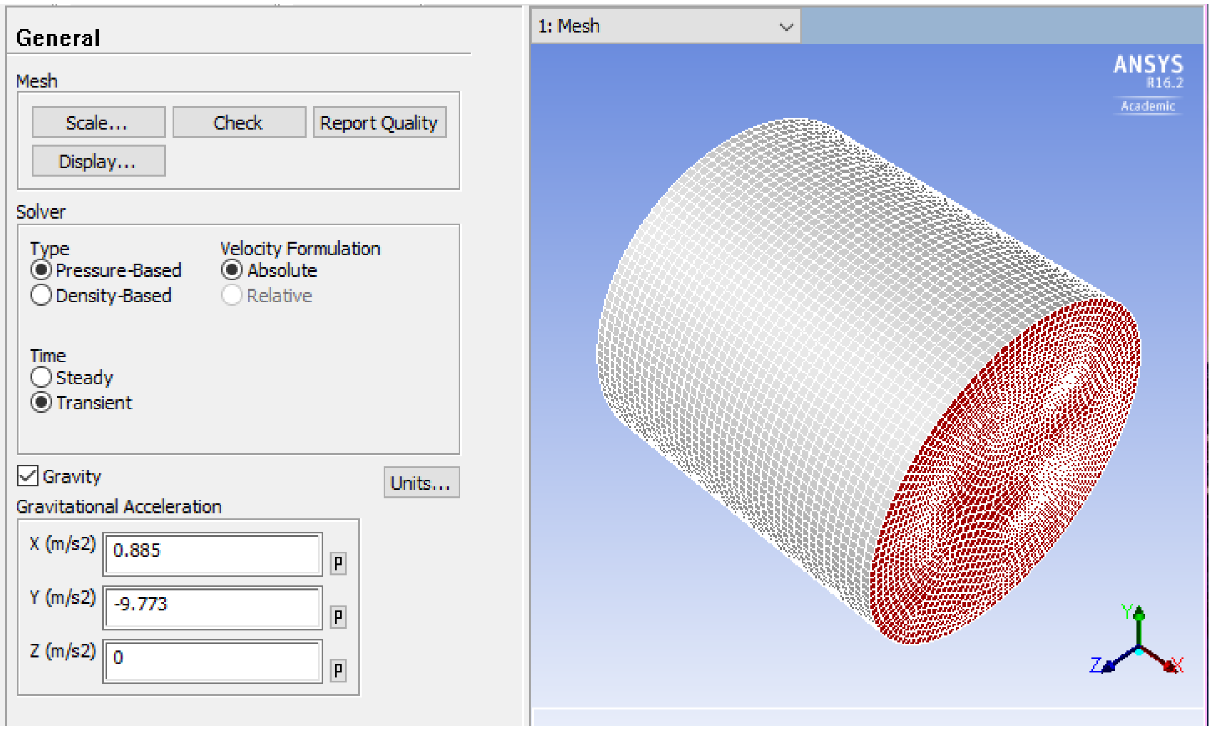
Then the named sections are created, in this case:

- Inlet
- Outlet
- Wall
- Fluid



Simulation 4 Named SEction.

The previous figure shows the named sections, more specifically the fluid one. Once the mesh is done it is exported using the Fluent import File format (*.msh).



General

Mesh

Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

☑ Gravity

Gravitational Acceleration
X (m/s2) 0.885
Y (m/s2) -9.773
Z (m/s2) 0

Simulation4 General Menu Fluent

-Genera

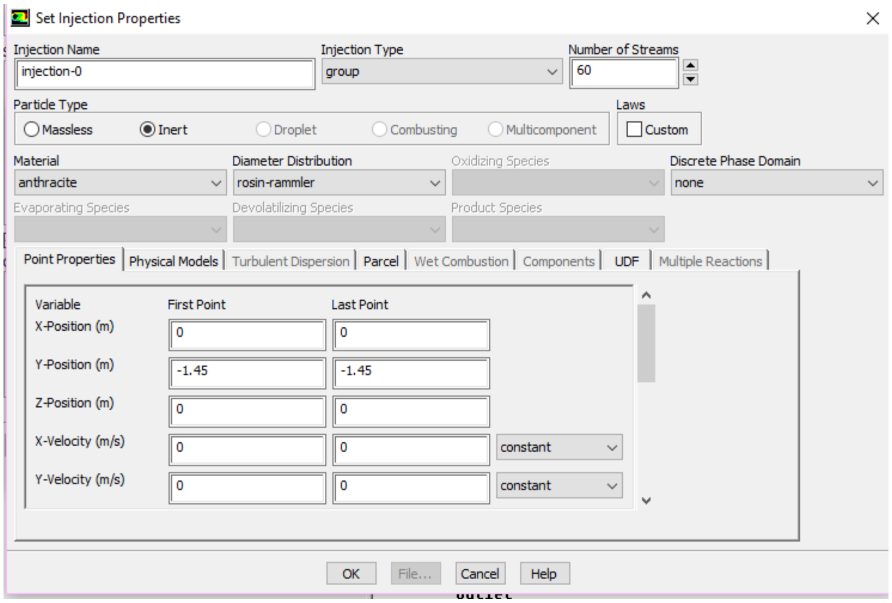
- Type: Pressure-Based
- Time: Transient
- Gravity: on
- X: 0.885
- Y: -9.773

-Models

- Discrete Phase: on
    - Interaction with continuous flow: on
    - Update DPM sources Every Flow Iteration
    - Number of continuous phase iterations per DPM iteration: 10
    - Unsteady particle tracking: on
    - Track with fluid time step: on
    - Max number of Steps: 500
    - Step length factor: 5
    - Parallel – Methods – Hybrid

- Injections
    - Number of streams: 60
    - Particle type: Inert
    - Material: anthracite
    - Diameter Distribution: Linear
    - Discrete phase Demine: None
    - First X-Position (m) :
    - Last X-Position (m) :
    - First Y-Position (m) : -1.45
    - Last Y-Position (m) : -1.45
    - Start Time (S): 0
    - Stop Time (S): 10000
    - Flow Rate: (Kg/S): 0.07
    - Min. Diameter (M): 0.001
    - Max. Diameter (M): 0.012
    - Mean. Diameter (M): 0.006
    - Spread Parameter: 3.5 (Default)

The injection are the way the software ANSYS call the introduction of the discrete phase particles to the system. The setting menu for them of show on the next figure:



Injection Name: injection-0
Injection Type: group
Number of Streams: 60
Particle Type: ○ Massless ● Inert ○ Droplet ○ Combusting ○ Multicomponent
Laws: ☐ Custom
Material: anthracite
Diameter Distribution: rosin-rammler
Oxidizing Species:
Discrete Phase Domain: none
Evaporating Species:
Devolatilizing Species:
Product Species:

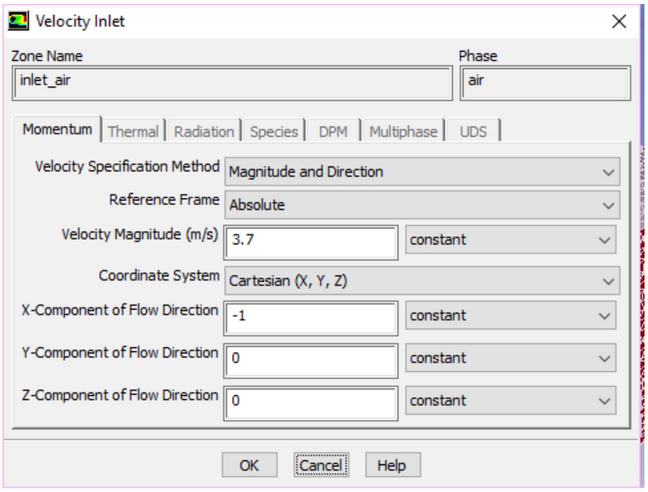
Variable	First Point	Last Point	
X-Position (m)	0	0	
Y-Position (m)	-1.45	-1.45	
Z-Position (m)	0	0	
X-Velocity (m/s)	0	0	constant
Y-Velocity (m/s)	0	0	constant

; Simulation4 Injections

The differences with the fist model, Particle size distribution and number of streams, are simplification of the model in order to compensate the increase on the mesh and simulation complexity.

- Materials
    - Fluid
        - Air
    - Solid
        - Aluminum
    - Inter Particle
        - Anthracite
            - Density: 1760 Kg/M3
- Boundary Conditions
    - Inlet Air: Phase Air
        - Velocity Specification Method: Magnitude and Direction
        - Velocity magnitude (M/S) 3.7
        - X-Component of Flow direction: -1
        - Y-Component of Flow direction: 0
        - Z-Component of Flow direction: 0
    - Wall: Phase Mixture
        - Momentum: Static
            - Z:0
        - DPM
            - Boundary Condition Type: Reflect
            - Discrete Phase Reflection Coefficient: Normal 0.75
            - Discrete Phase Reflection Coefficient: Tangential 0.8

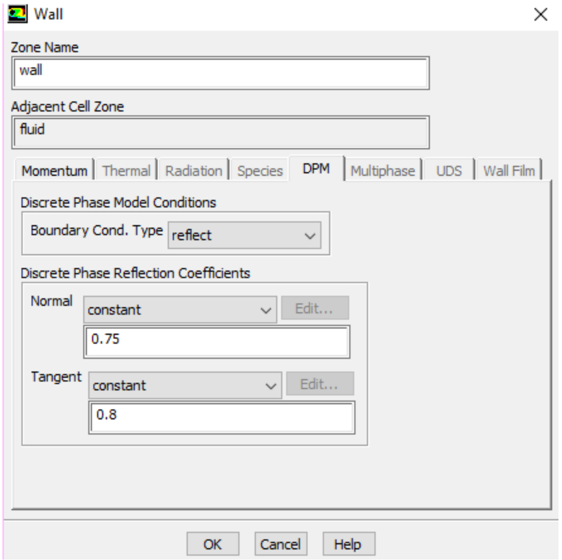
On the boundary condition menu, for the inlet air, the velocity and direction of the air as well as its multiphase ratio, if necessary, can be specified as shown on the next menu



Zone Name: inlet_air
Phase: air
Velocity Specification Method: Magnitude and Direction
Reference Frame: Absolute
Velocity Magnitude (m/s): 3.7 constant
Coordinate System: Cartesian (X, Y, Z)
X-Component of Flow Direction: -1 constant
Y-Component of Flow Direction: 0 constant
Z-Component of Flow Direction: 0 constant

; Simulation4 Boundary Conditions Air

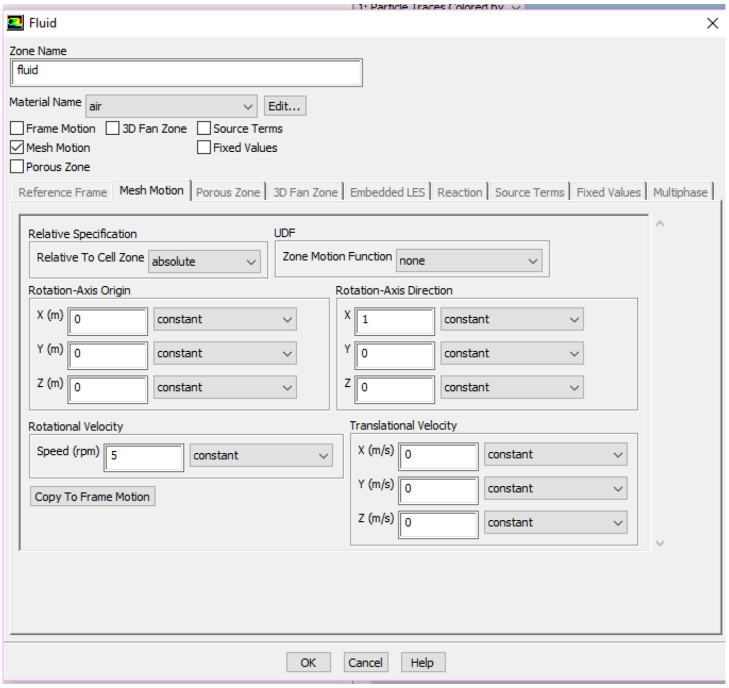
The values of the DPM menu for, Discrete phase Reflection Coefficient are very important because they will determine the behavior of the particles, they can be set as shown on the nest figure.



Zone Name: wall
Adjacent Cell Zone: fluid
Discrete Phase Model Conditions
Boundary Cond. Type: reflect
Discrete Phase Reflection Coefficients
Normal: constant 0.75
Tangent: constant 0.8

Simulation4 DPM coefficients

In order to achieve the rotation of the system on the Cell Zone condition section the next changed were made for the fluid zone:



Zone Name: fluid
Material Name: air
☐ Frame Motion ☐ 3D Fan Zone ☐ Source Terms
☑ Mesh Motion ☐ Fixed Values
☐ Porous Zone

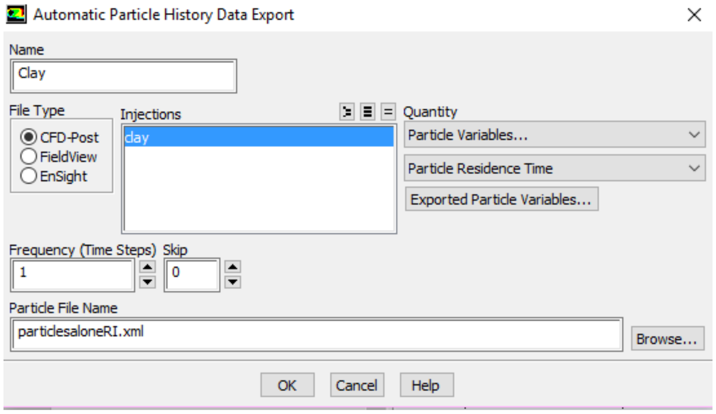
Relative Specification: Relative To Cell Zone: absolute
UDF: Zone Motion Function: none

Rotation-Axis Origin: X (m) 0 constant; Y (m) 0 constant; Z (m) 0 constant
Rotation-Axis Direction: X 1 constant; Y 0 constant; Z 0 constant
Rotational Velocity: Speed (rpm) 5 constant
Translational Velocity: X (m/s) 0 constant; Y (m/s) 0 constant; Z (m/s) 0 constant

Simulation4 Moving Cells Zones

On the boundary condition menu, for the wall, the velocity and direction of the rotation can be specified, where the value of -1 or 1 will indicate the clock or anti clock wise rotation, as shown on the previous figure.

An Automatic Particle Export Data file was created, saving the Residence time of the particles, diameter and position among the X axis. As Shown on the figure

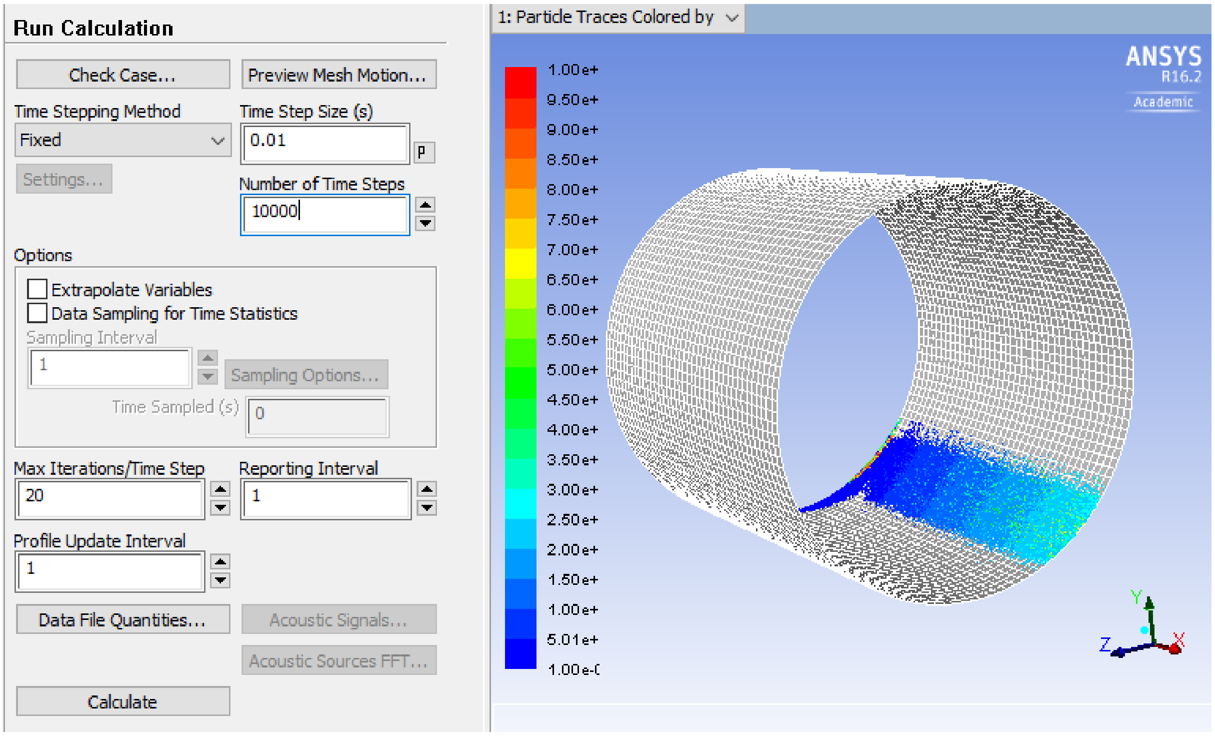


Name: Clay
File Type: ● CFD-Post ○ FieldView ○ EnSight
Injections: clay
Quantity: Particle Variables... / Particle Residence Time
Frequency (Time Steps): 1
Skip: 0
Particle File Name: particlesaloneRI.xml

; Simulation4 Particle File

Simulation Running time

The simulation was Run for 100 seconds with a time step of 0.005 Seconds and 25 interactions per time step.



Run Calculation

Time Stepping Method: Fixed

Time Step Size (s): 0.01

Number of Time Steps: 10000

Options

☐ Extrapolate Variables

☐ Data Sampling for Time Statistics

Sampling Interval: 1

Time Sampled (s): 0

Max Iterations/Time Step: 20

Reporting Interval: 1

Profile Update Interval: 1

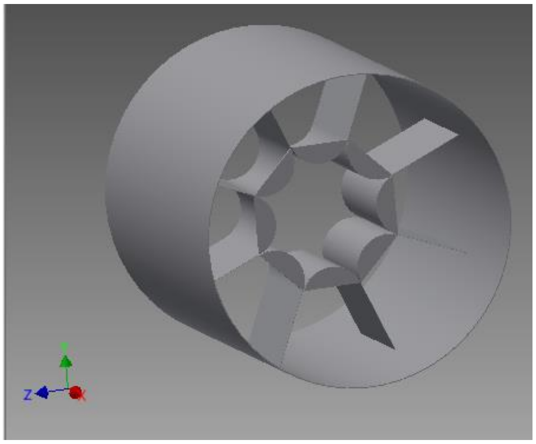
Simulation4 Time Step

Simulation 3

For the first simulation, as mention before, The internal construction of the real kiln will be simulated, and the rotation of the system was achieved with the moving frame option, in other words, the mesh is moving. The full simulation process is the next one:

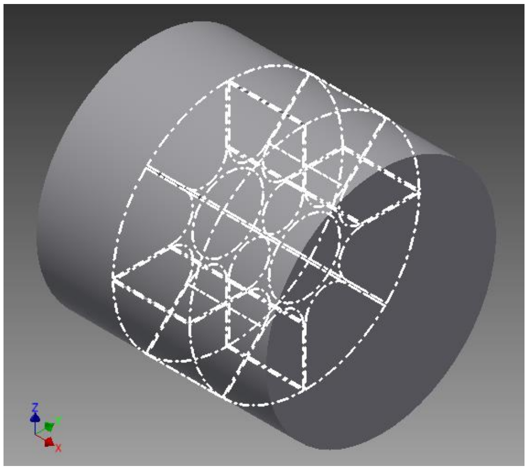
3D Drawing

First using the software Inventor professional 2015 with academic license, a 3-meter section of the kiln was drawn.



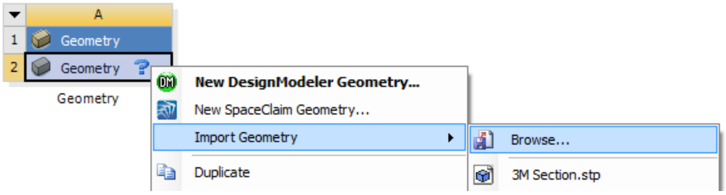
Simulation 2 kiln Extrusion

But in order to be able to simulate the process a negative version of it has to be created where only the empty space is filled, and the wall are cut, hiding the internal construction inside the geometry



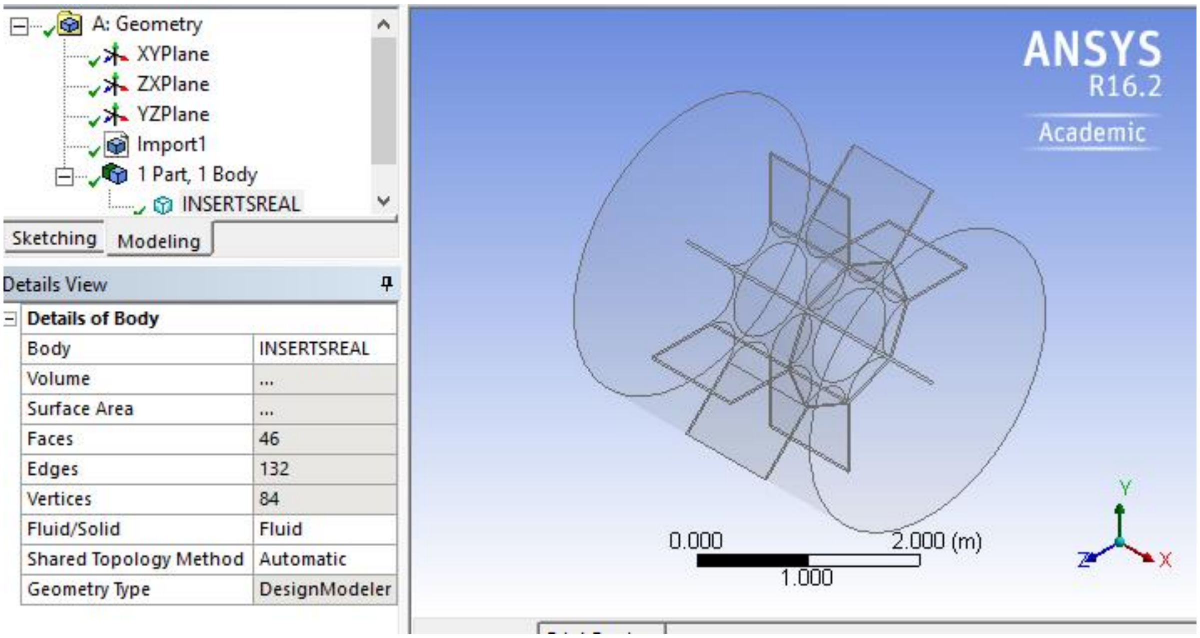
; Simulation 2 kiln Internal shape

The resulting body was saved on Step format (*.stp). For then being opened on the Ansys 16.2 software on the geometry tool as shown in the figure 61



Simulation 2 Geometry Exporting

Once the file is load, it was opened on the geometry tool, where the part was changed from solid to fluid, on the details of body menu as shown on the picture

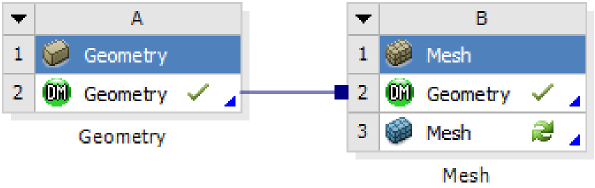


Details of Body	
Body	INSERTSREAL
Volume	...
Surface Area	...
Faces	46
Edges	132
Vertices	84
Fluid/Solid	Fluid
Shared Topology Method	Automatic
Geometry Type	DesignModeler

Simulation 2 Solid/Fluid

Mesh

Then the Meshing tool was called to into the project schematics as the following step.

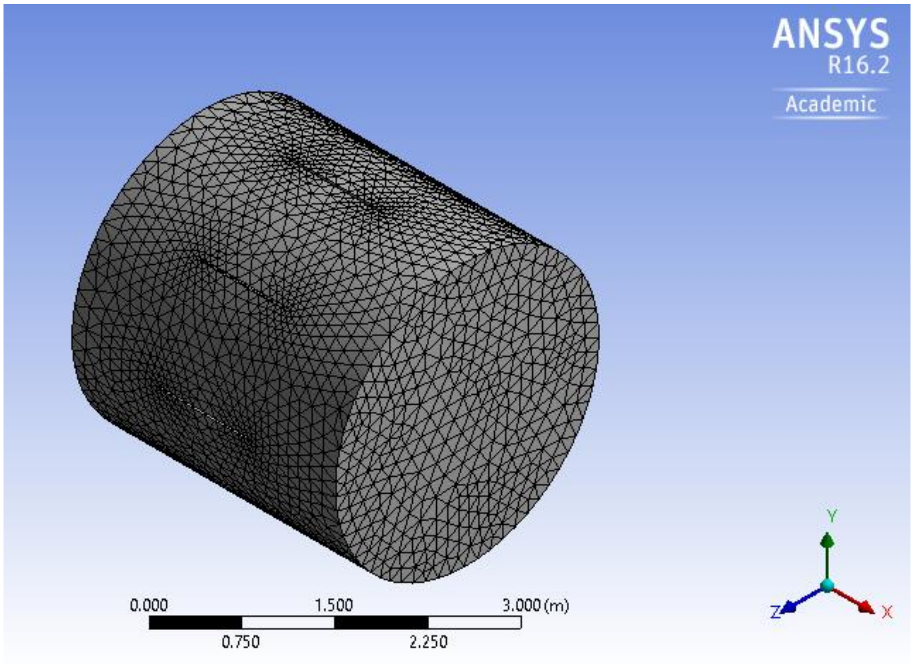


Simulation 2 Project Bench

The mesh was generated changing the following options on the details of mesh menu:

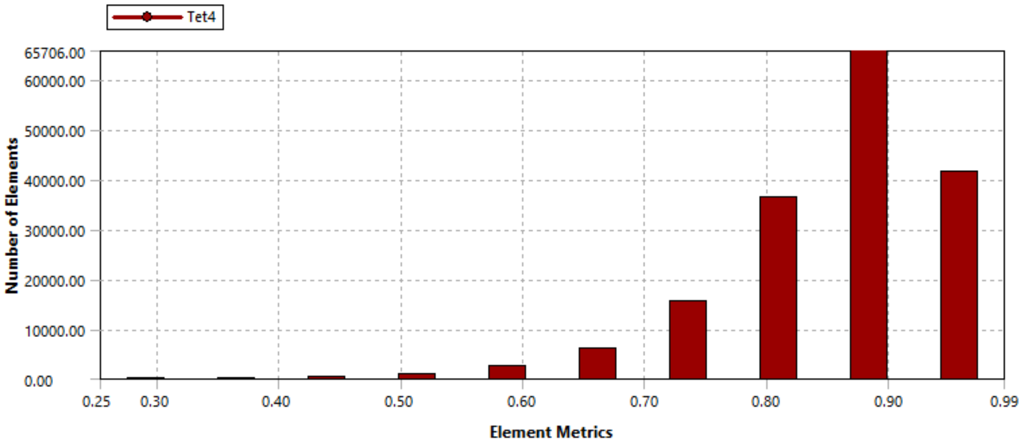
1.- Physical References: CFD
2.- Solver Preferences: Fluent
3.- Use advance Size Function: on: Proximity and curvature
4.- Relevance Center: Fine
5.- Smoothing: High

The rest of the option where left on default settings, the generated mesh is shown in the next figure ***



Simulation 2 Meshing

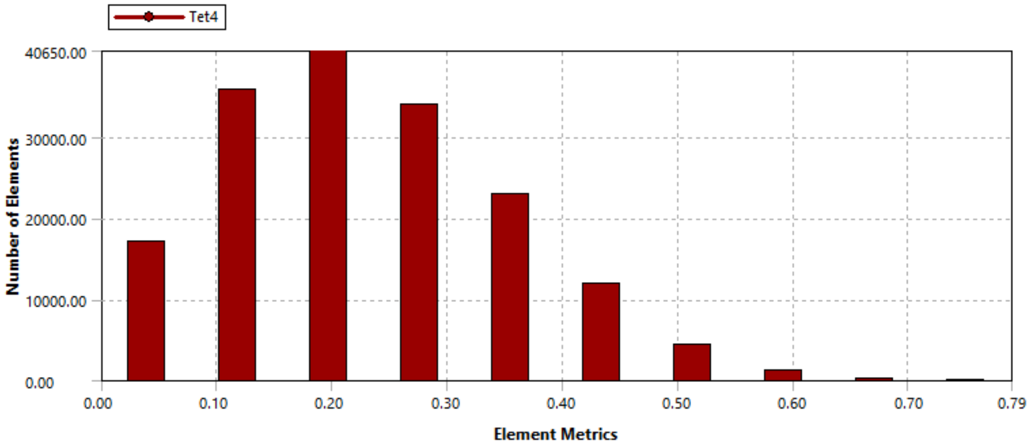
This mesh has the following orthogonal quality values, shown on the next figure:



Simulation 2 Orthogonal Quality

- Nodes: 31,011
- Elements: 158, 589
- Mesh metrics, orthogonal quality:
- Min 0.25293
- Max: 0.99473
- Average 0.85719
- Standard Deviation: 8.5086e-002

And a under the skewedness measurement, as shown on the next figure:



Simulation 2 Skewness

- Min: 1.0801e-004
- Max: 0.7896

- Average: 0.23058
- Standard Deviation: 0.12201

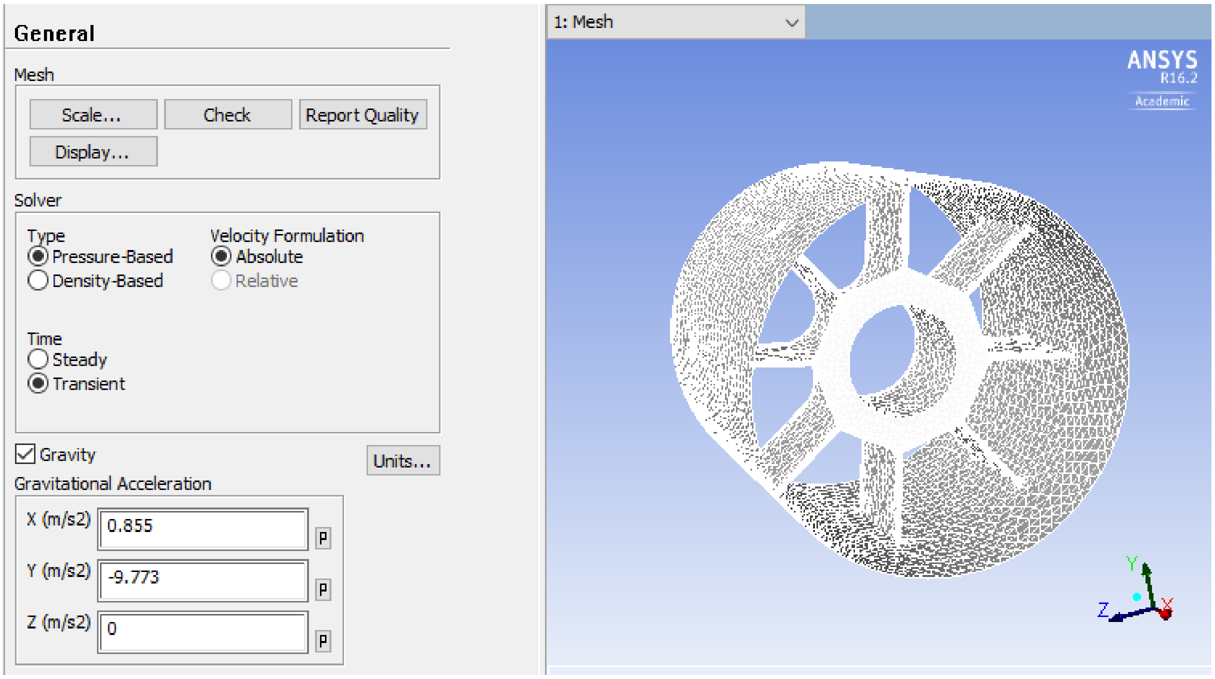
Then the named sections are created, in this case:

- Inlet
- Outlet
- Wall
- Fluid

It is important for the wall Named section to select the 46 faces of the wall, in order to fully recreated the wall. Once the mesh is done it is exported using the Fluent import File format (*.msh).

Fluent

The mesh file is imported to fluent where the settings were done as shown the next sequence.



Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

☑ Gravity

Gravitational Acceleration
X (m/s2) 0.855
Y (m/s2) -9.773
Z (m/s2) 0

Simulation 2 General Menu Fluent

-Genera

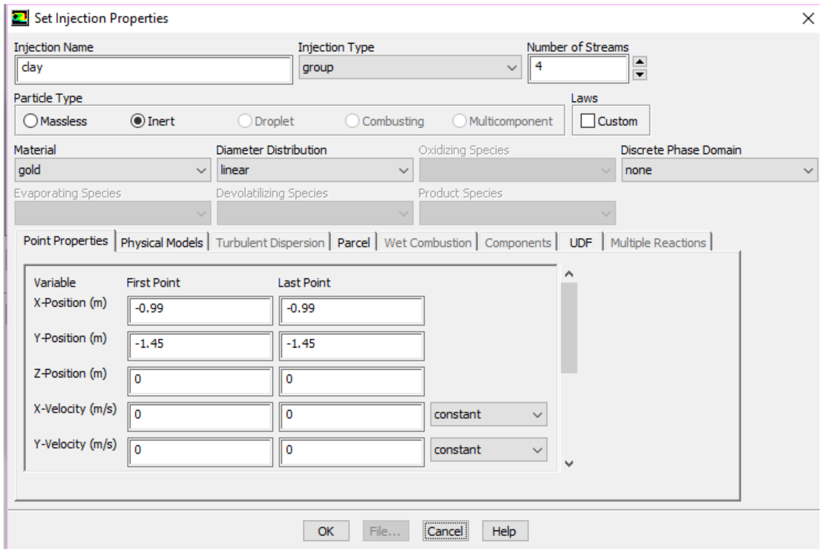
- Type: Pressure-Based
- Time: Transient
- Gravity: on
- X: 0.885
- Y: -9.773

-Models

- Discrete Phase: on
    - Interaction with continuous flow: on
    - Update DPM sources Every Flow Iteration
    - Number of Continuous phase iterations per DPM iteration: 10
    - Unsteady particle tracking: on
    - Track with fluid time step: on
    - Max number of Steps: 500
    - Step length factor: 5
    - Parallel – Methods – Hybrid

- Injections
    - Number of streams: 4
    - Particle type: Inert
    - Material: Gold
    - Diameter Distribution: Linear
    - Discrete phase Demine: None
    - First X-Position (m) : -0.99
    - Last X-Position (m) : 0.-99
    - First Y-Position (m) : -1.45
    - Last Y-Position (m) : -1.45
    - Start Time (s): 0
    - Stop Time (s): 10000
    - Flow Rate: (kg/s): 0.07
    - Min. Diameter (m): 0.001
    - Max. Diameter (m): 0.012
    - Mean. Diameter (m): 0.006
    - Spread Parameter: 3.5 (Default)

The injection is the way the software ANSYS call the introduction of the discrete phase particles to the system. The setting menu for them of show on the next figure:



Injection Name: clay
Injection Type: group
Number of Streams: 4
Particle Type: ○ Massless ● Inert ○ Droplet ○ Combusting ○ Multicomponent
Laws: ☐ Custom
Material: gold
Diameter Distribution: linear
Oxidizing Species:
Discrete Phase Domain: none
Evaporating Species:
Devolatilizing Species:
Product Species:

Variable	First Point	Last Point	
X-Position (m)	-0.99	-0.99	
Y-Position (m)	-1.45	-1.45	
Z-Position (m)	0	0	
X-Velocity (m/s)	0	0	constant
Y-Velocity (m/s)	0	0	constant

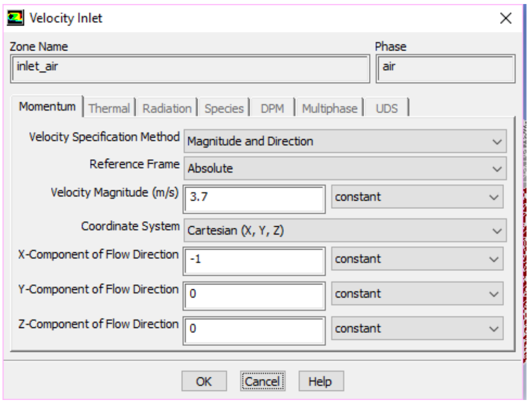
Simulation 2 Injections

The differences with the first model, Particle size distribution and number of streams, are simplification of the model in order to compensate the increase on the mesh and simulation complexity.

- Materials
  - Fluid
    - Air
  - Solid
    - Aluminum
  - Inter Particle
    - Gold
      - Density: 1760 kg/m3
- Boundary Conditions
  - Inlet Air: Phase Air
    - Velocity Specification Method: Magnitude and Direction
    - Velocity magnitude (m/s) 3.7
    - X-Component of Flow direction: -1
    - Y-Component of Flow direction: 0
    - Z-Component of Flow direction: 0
  - Wall: Phase Mixture
    - Momentum: Static
      - Z:0
    - DPM
      - Boundary Condition Type: Reflect
      - Discrete Phase Reflection Coefficient: Normal 0.75
      - Discrete Phase Reflection Coefficient: Tangential 0.8

In the boundary condition menu, for the inlet air, the velocity and direction of the air as well as its multiphase ratio, if necessary, can be specified as shown on the next menu

In the boundary condition menu, for the inlet air, the velocity and direction of the air as well as its multiphase ratio, if necessary, can be specified as shown on the next menu



Velocity Inlet

Zone Name: inlet_air

Phase: air

Velocity Specification Method: Magnitude and Direction

Reference Frame: Absolute

Velocity Magnitude (m/s): 3.7 constant

Coordinate System: Cartesian (X, Y, Z)

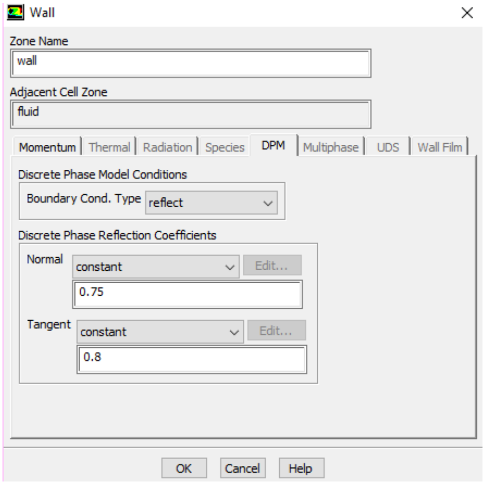
X-Component of Flow Direction: -1 constant

Y-Component of Flow Direction: 0 constant

Z-Component of Flow Direction: 0 constant

Simulation 2 Boundary Conditions Air

The values of the DPM menu for, Discrete phase Reflection Coefficient are very important because they will determine the behavior of the particles, they can be set as shown on the nest figure.



Wall

Zone Name: wall

Adjacent Cell Zone: fluid

Discrete Phase Model Conditions

Boundary Cond. Type: reflect

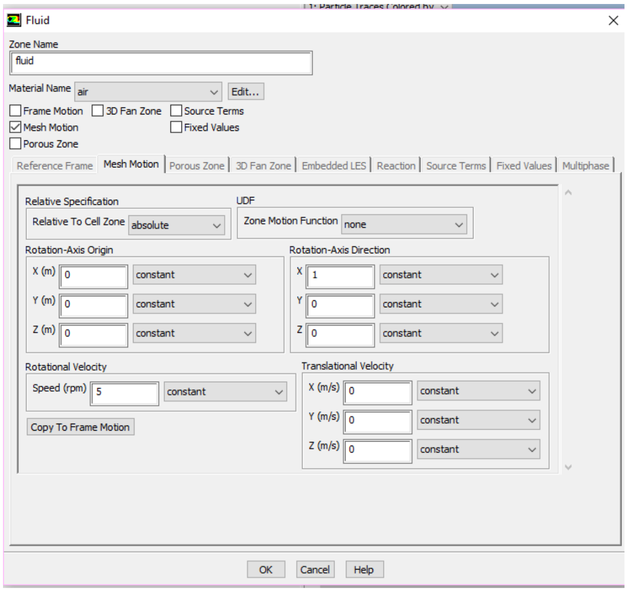
Discrete Phase Reflection Coefficients

Normal: constant 0.75

Tangent: constant 0.8

:Simulation 2 DPM coefficients

In order to achieve the rotation of the system on the Cell Zone condition section the next changed were made for the fluid zone:



Zone Name: fluid

Material Name: air

☐ Frame Motion ☐ 3D Fan Zone ☐ Source Terms

☑ Mesh Motion ☐ Fixed Values

☐ Porous Zone

Relative Specification – Relative To Cell Zone: absolute

UDF – Zone Motion Function: none

Rotation-Axis Origin

X (m): 0 constant

Y (m): 0 constant

Z (m): 0 constant

Rotation-Axis Direction

X: 1 constant

Y: 0 constant

Z: 0 constant

Rotational Velocity – Speed (rpm): 5 constant

Translational Velocity

X (m/s): 0 constant

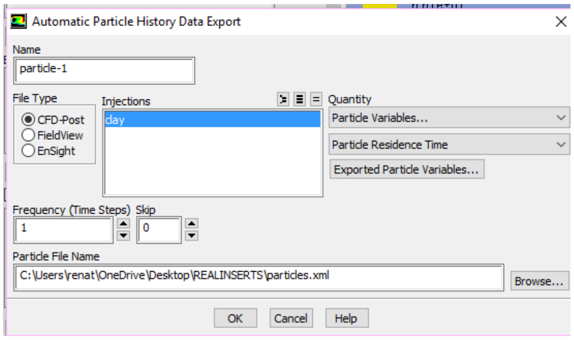
Y (m/s): 0 constant

Z (m/s): 0 constant

Simulation 2 Moving Cells Zones

On the boundary condition menu, for the wall, the velocity and direction of the rotation can be specified, where the value of -1 or 1 will indicate the clock or anti clock wise rotation, as shown on the previous figure.

An Automatic Particle Export Data file was created, saving the Residence time of the particles, diameter and position among the X axis. As Shown on the figure



Name: particle-1

File Type: ● CFD-Post ○ FieldView ○ EnSight

Injections: clay

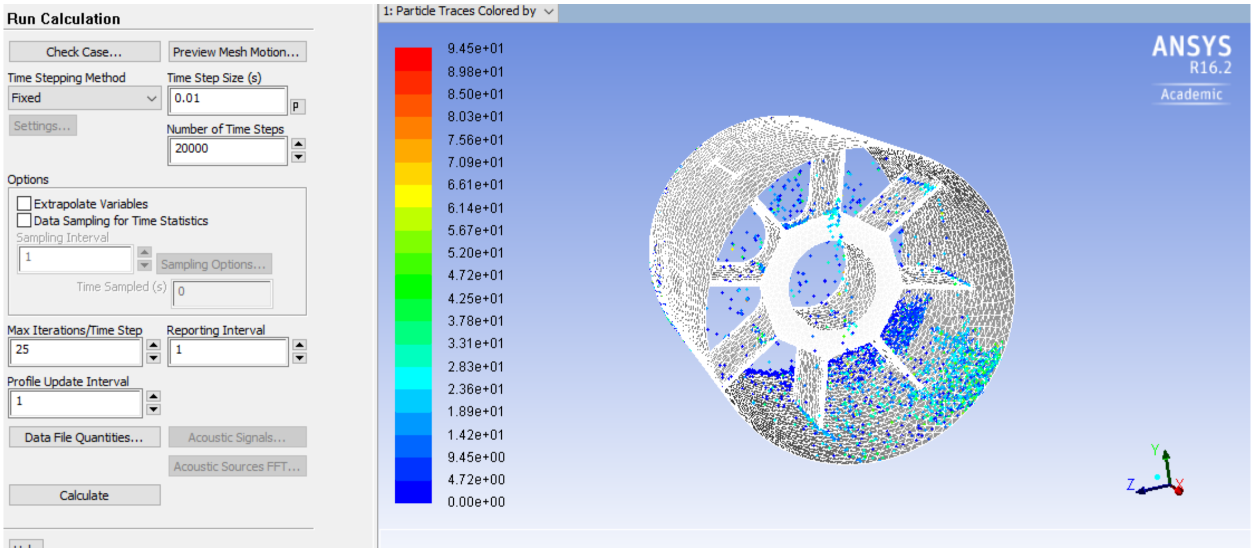
Quantity: Particle Variables... / Particle Residence Time

Frequency (Time Steps): 1 Skip: 0

Particle File Name: C:\Users\renat\OneDrive\Desktop\REALINSERTS\particles.xml

: Simulation 2 Particle File

The simulation was Run for 100 seconds with a time step of 0.01 Seconds and 25 interactions per time step.



Run Calculation

Time Stepping Method: Fixed

Time Step Size (s): 0.01

Number of Time Steps: 20000

Options

☐ Extrapolate Variables

☐ Data Sampling for Time Statistics

Sampling Interval: 1

Time Sampled (s): 0

Max Iterations/Time Step: 25

Reporting Interval: 1

Profile Update Interval: 1

Simulation 2 Time Step

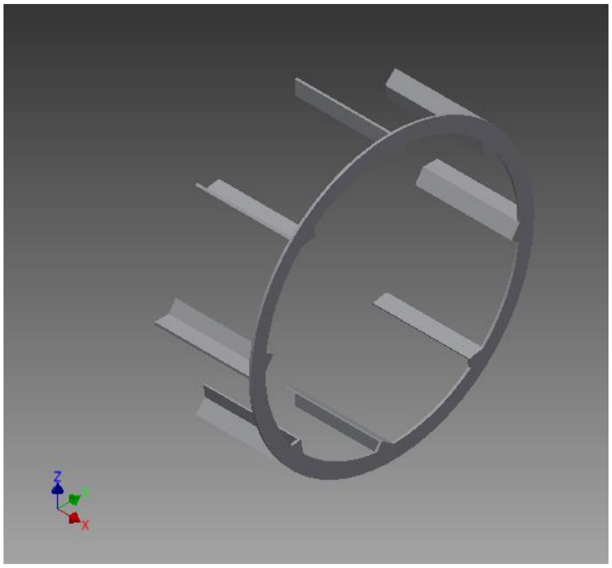
Simulation 4

Simulation 3

For the first simulation, as mention before. The internal construction of the real kiln will be simulated, and the rotation of the system was achieved with the moving frame option, in other words, the mesh is moving. The full simulation process is the next one:

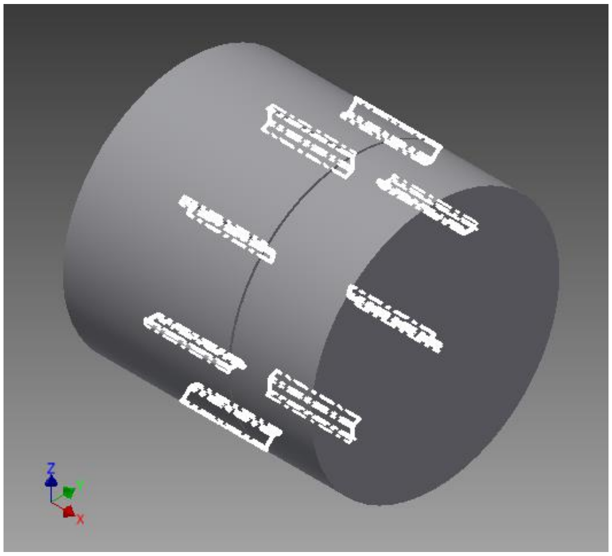
3D Drawing

First using the software Inventor professional 2015 with academic license, a 3-meter section of the kiln was drawn.



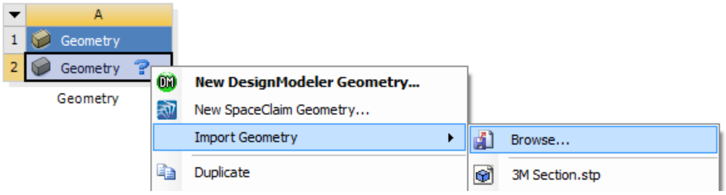
Simulation3 Kiln Extrusion

But in other to be able to simulate the process a negative version of it has to be created where only the empty space is filled, and the wall are cut, hiding the internal construction inside the geometry



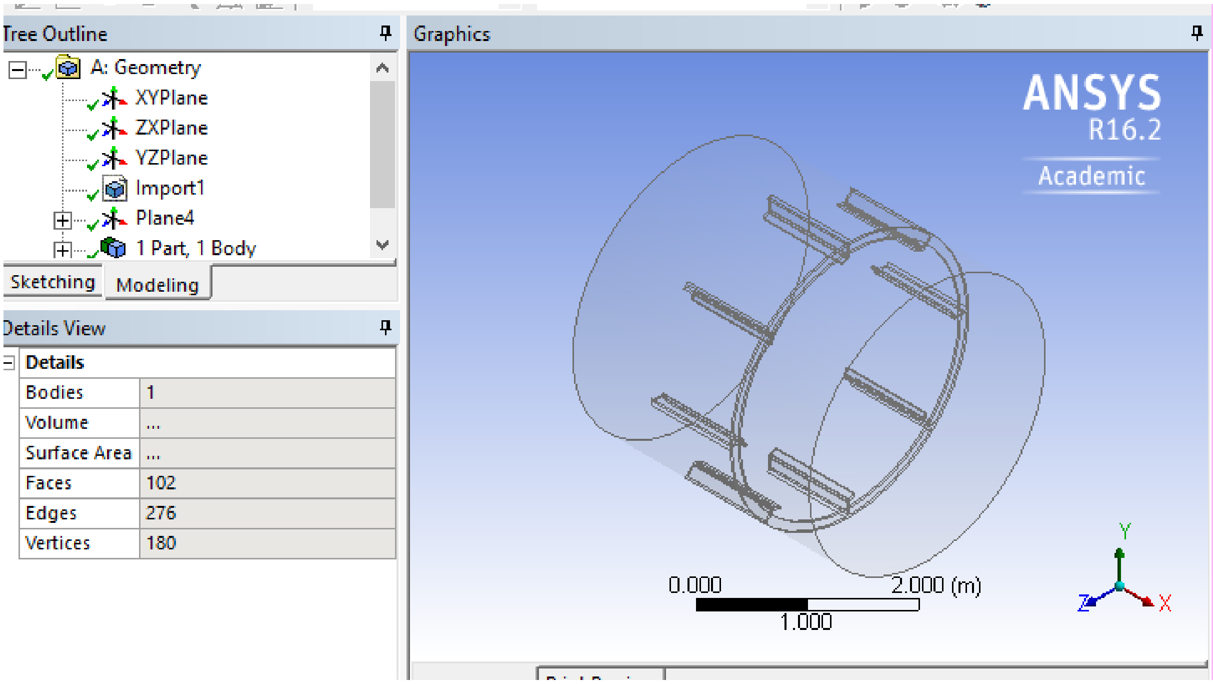
Simulation3 Kiln Internal shape

The resulting body was saved on Step format (*.stp). It has been opened on the Ansys 16.2 software on the geometry tool as shown in the figure ****



Simulation 3 Geometry Exporting

Once the file is loaded, it was opened on the geometry tool, where the part was changed from solid to fluid, on the details of body menu as shown in the picture



Tree Outline

- A: Geometry
  - XYPlane
  - ZXPlane
  - YZPlane
  - Import1
  - Plane4
  - 1 Part, 1 Body

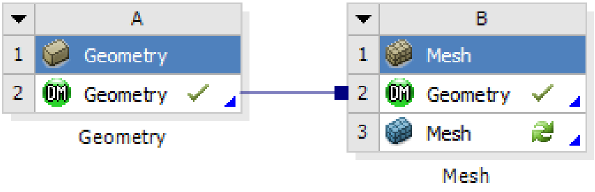
Details View

Details	
Bodies	1
Volume	...
Surface Area	...
Faces	102
Edges	276
Vertices	180

Simulation3 Solid/Fluid

Mesh

Then the Meshing tool was called to into the project schematics as the following step.

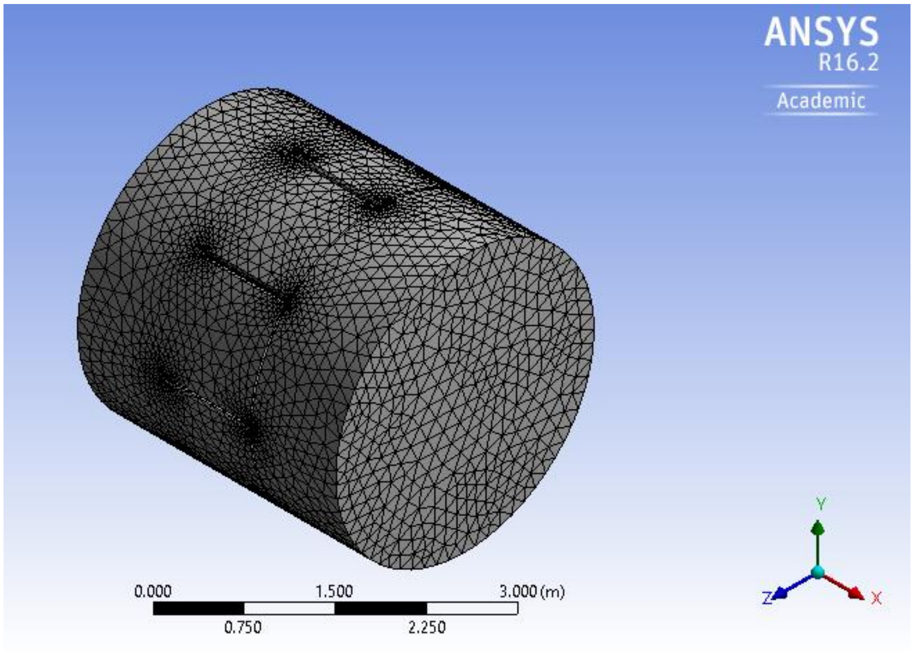


Simulation3 Project Bench

The mesh was generated changing the following options on the details of mesh menu:

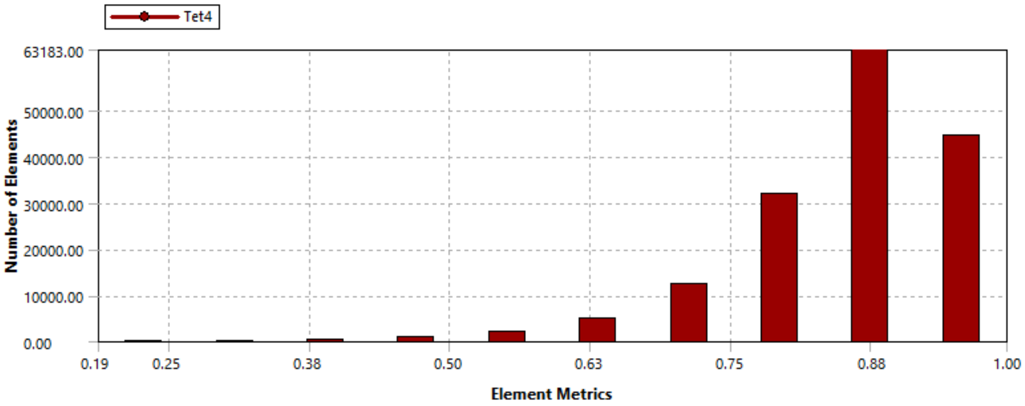
1.- Physical References: CFD
2.- Solver Preferences: Fluent
3.- Use advance Size Function: on: Proximity and curvature
4.- Relevance Center: Fine
5.- Smoothing: High

The rest of the option where left on default settings, the generated mesh is shown in the next figure 79.



Simulation 3 Meshing

This mesh has the following orthogonal quality values, shown on the next figure:

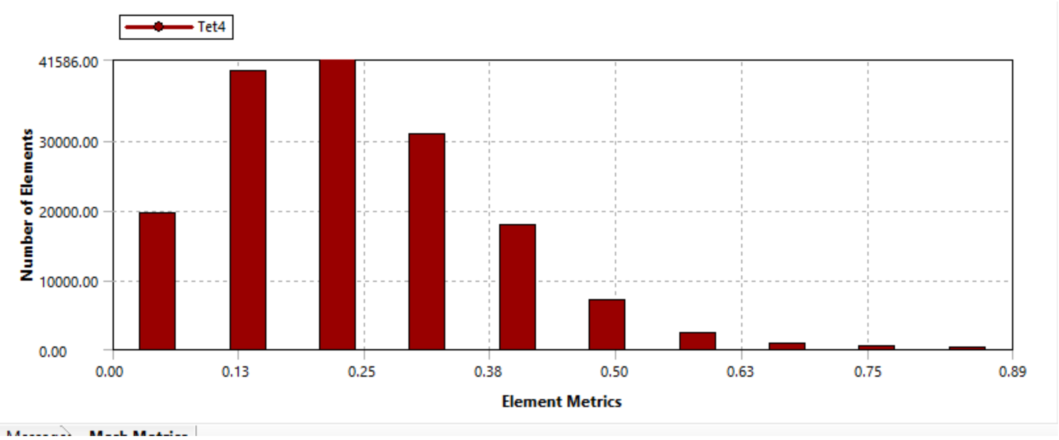


Simulation 3 Orthogonal Quality

- Nodes: 30,173
- Elements: 159, 940
- Mesh metrics, orthogonal quality:
- Min 0.18692
- Max: 0.99566
- Average 0.85304

- Standard Deviation: 9.2512e-002

And a under the skewedness measurement, as shown on the next figure:

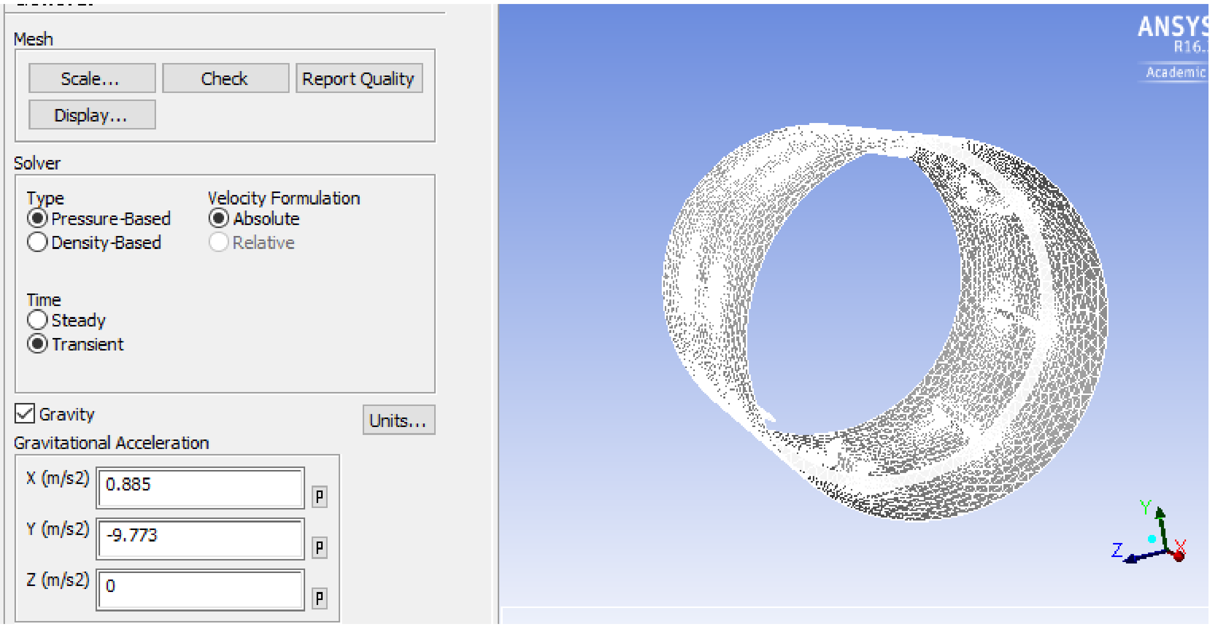


; Simulation 3 Skewness

Then the named sections are created, in this case:

- Inlet
- Outlet
- Wall
- Fluid

It is important for the wall Named section to select the 102 faces of the wall, in order to fully recreated the wall. Once the mesh is done it is exported using the Fluent import File format (*.msh).



Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

☑ Gravity

Gravitational Acceleration

X (m/s2) 0.885
Y (m/s2) -9.773
Z (m/s2) 0

Simulation3 General Menu Fluent

-Genera

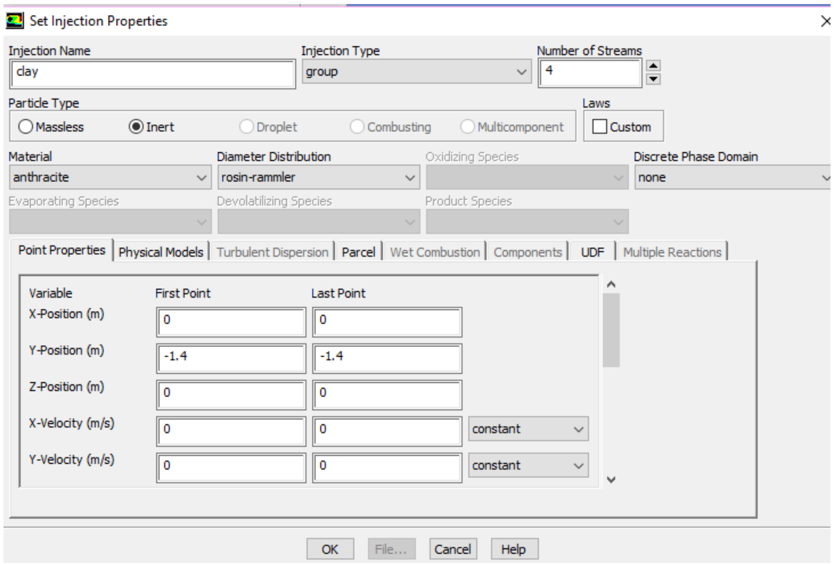
- Type: Pressure-Based
- Time: Transient
- Gravity: on
- X: 0.885
- Y: -9.773

-Models

- Discrete Phase: on
    - Interaction with continuos flow: on
    - Update DPM sources Every Flow Iteration
    - Number of Continuos phase iterations per DPM iteration: 10
    - Unsyeady particle tracking: on
    - Track with fluid time step: on
    - Max number of Steps: 500
    - Step length factor: 5
    - Parallel – Methods – Hybrid

- Injections
    - Number of streams: 4
    - Particle type: Inert
    - Material: Gold
    - Diameter Distribution: Linear
    - Discrete phase Demine: None
    - First X-Position (m) :
    - Last X-Position (m) :
    - First Y-Position (m) : -1.45
    - Last Y-Position (m) : -1.45
    - Start Time (S): 0
    - Stop Time (S): 10000
    - Flow Rate: (Kg/S): 0.07
    - Min. Diameter (M): 0.001
    - Max. Diameter (M): 0.012
    - Mean. Diameter (M): 0.006
    - Spread Parameter: 3.5 (Default)

The injection are the way the software ANSYS call the introduction of the discrete phase particles to the system. The setting menu for them of show on the next figure:



Injection Name: clay
Injection Type: group
Number of Streams: 4
Particle Type: ○ Massless ● Inert ○ Droplet ○ Combusting ○ Multicomponent
Laws: ☐ Custom
Material: anthracite
Diameter Distribution: rosin-rammler
Oxidizing Species:
Discrete Phase Domain: none
Evaporating Species:
Devolatilizing Species:
Product Species:

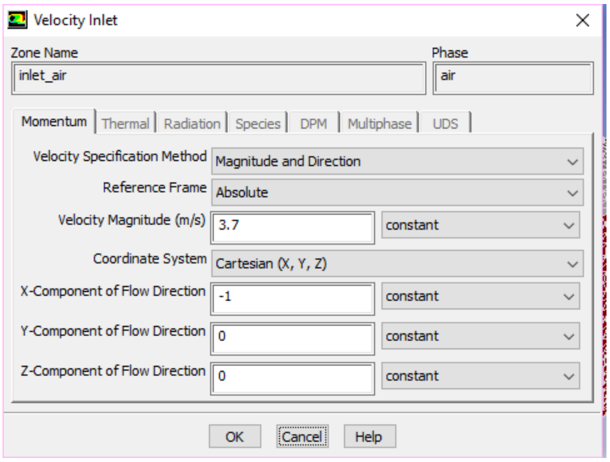
Variable	First Point	Last Point	
X-Position (m)	0	0	
Y-Position (m)	-1.4	-1.4	
Z-Position (m)	0	0	
X-Velocity (m/s)	0	0	constant
Y-Velocity (m/s)	0	0	constant

Simulation3 Injections

The differences with the fist model, Particle size distribution and number of streams, are reduced in the model in order to compensate the increase on the mesh and simulation complexity.

- Materials
  - Fluid
    - Air
  - Solid
    - Aluminum
  - Inter Particle
    - Anthracite
      - Density: 1760 Kg/M3
- Boundary Conditions
  - Inlet Air: Phase Air
    - Velocity Specification Method: Magnitude and Direction
    - Velocity magnitude (M/S) 3.7
    - X-Component of Flow direction: -1
    - Y-Component of Flow direction: 0
    - Z-Component of Flow direction: 0
  - Wall: Phase Mixture
    - Momentum: Static
      - Z:0
    - DPM
      - Boundary Condition Type: Reflect
      - Discrete Phase Reflection Coefficient: Normal 0.75
      - Discrete Phase Reflection Coefficient: Tangential 0.8

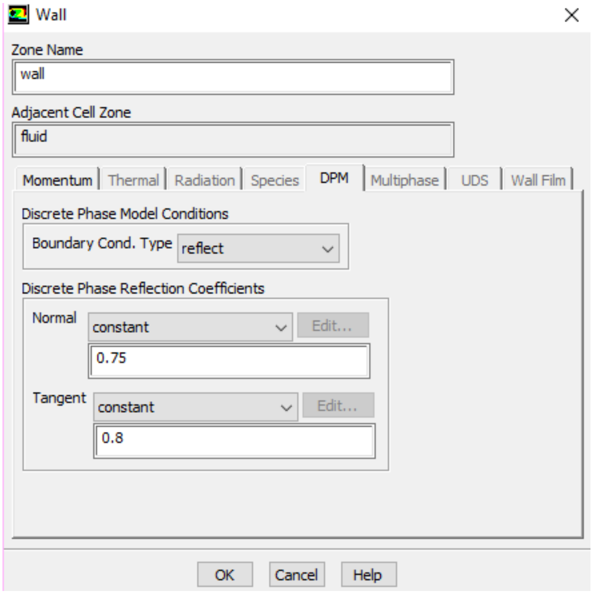
On the boundary condition menu, for the inlet air, the velocity and direction of the air as well as its multiphase ratio, if necessary, can be specified as shown on the next menu



Zone Name: inlet_air
Phase: air
Velocity Specification Method: Magnitude and Direction
Reference Frame: Absolute
Velocity Magnitude (m/s): 3.7 constant
Coordinate System: Cartesian (X, Y, Z)
X-Component of Flow Direction: -1 constant
Y-Component of Flow Direction: 0 constant
Z-Component of Flow Direction: 0 constant

Simulation3 Boundary Conditions Air

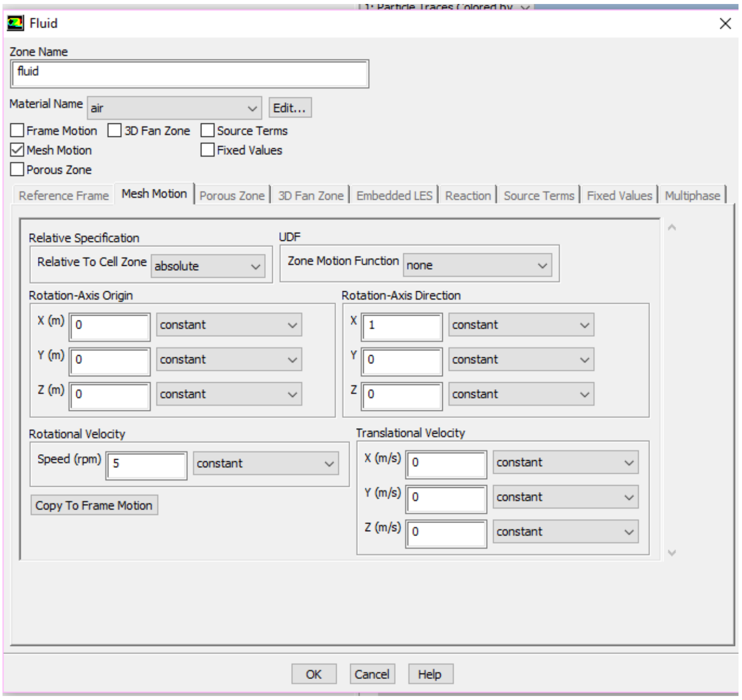
The values of the DPM menu for, Discrete phase Reflection Coefficient are very important because they will determine the behavior of the particles, they can be set as shown on the nest figure.



Zone Name: wall
Adjacent Cell Zone: fluid
Discrete Phase Model Conditions
Boundary Cond. Type: reflect
Discrete Phase Reflection Coefficients
Normal: constant 0.75
Tangent: constant 0.8

Simulation3 DPM coefficients

In order to achieve the rotation of the system on the Cell Zone condition section the next changed were made for the fluid zone:


Fluid

Zone Name: fluid

Material Name: air

☐ Frame Motion ☐ 3D Fan Zone ☐ Source Terms

☑ Mesh Motion ☐ Fixed Values

☐ Porous Zone

Relative Specification: Relative To Cell Zone: absolute

UDF: Zone Motion Function: none

Rotation-Axis Origin: X (m) 0 constant; Y (m) 0 constant; Z (m) 0 constant

Rotation-Axis Direction: X 1 constant; Y 0 constant; Z 0 constant

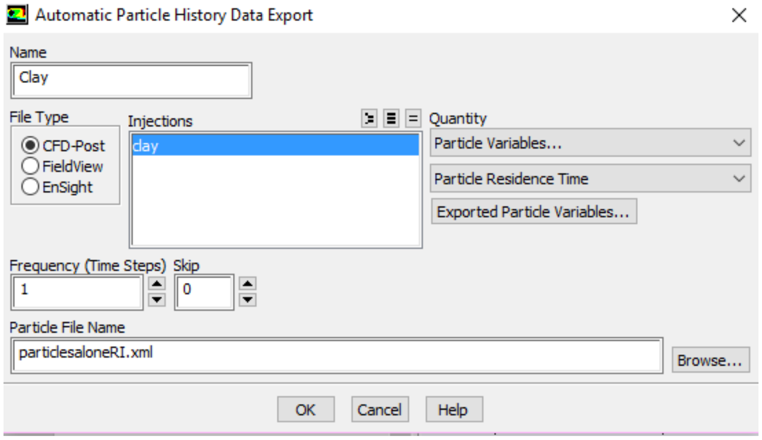
Rotational Velocity: Speed (rpm) 5 constant

Translational Velocity: X (m/s) 0 constant; Y (m/s) 0 constant; Z (m/s) 0 constant

Simulation3 Moving Cells Zones

On the boundary condition menu, for the wall, the velocity and direction of the rotation can be specified, where the value of -1 or 1 will indicate the clock or anti clock wise rotation, as shown on the previous figure.

An Automatic Particle Export Data file was created, saving the Residence time of the particles, diameter and position among the X axis. As Shown on the figure


Automatic Particle History Data Export

Name: Clay

File Type: ● CFD-Post ○ FieldView ○ EnSight

Injections: clay

Quantity: Particle Variables...

Particle Residence Time

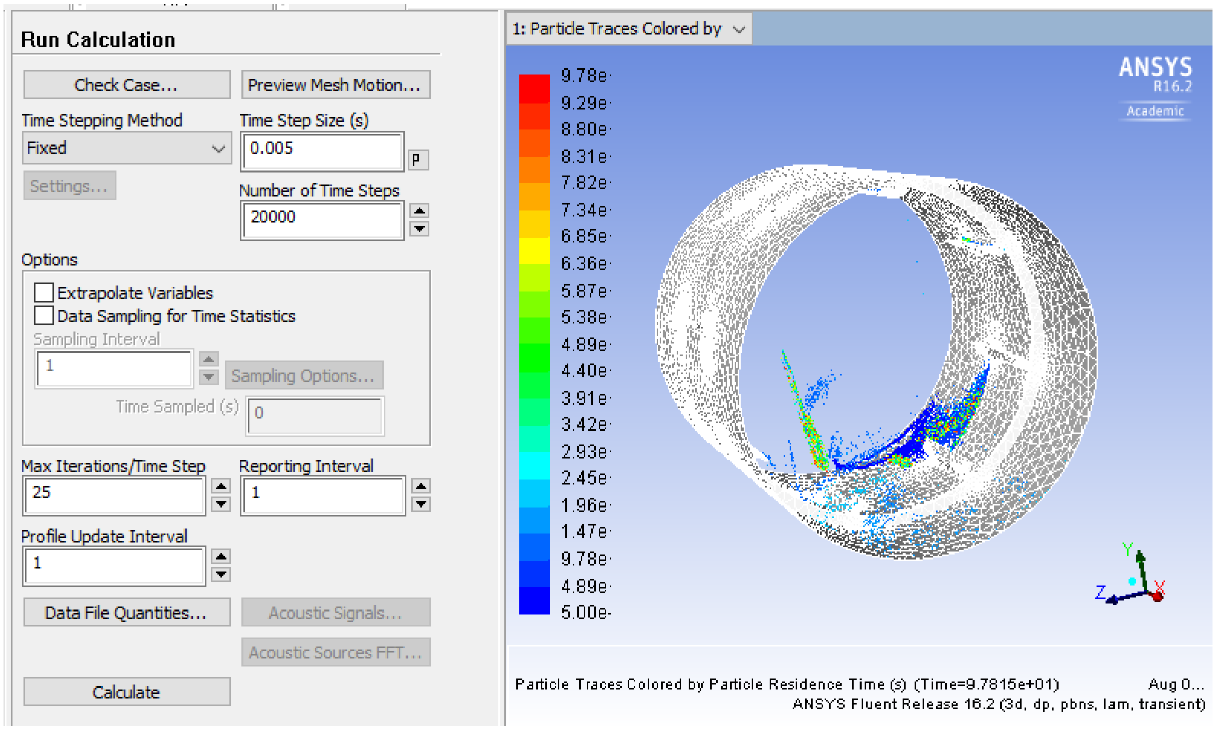
Frequency (Time Steps): 1 Skip: 0

Particle File Name: particlesaloneRI.xml

; Simulation3 Particle File

Simulation Running time

The simulation was Run for 100 seconds with a time step of 0.005 Seconds and 25 interactions per time step.



Time Stepping Method: Fixed
Time Step Size (s): 0.005
Number of Time Steps: 20000
☐ Extrapolate Variables
☐ Data Sampling for Time Statistics
Sampling Interval: 1
Time Sampled (s): 0
Max Iterations/Time Step: 25
Reporting Interval: 1
Profile Update Interval: 1

Particle Traces Colored by Particle Residence Time (s) (Time=9.7815e+01) Aug 0...
ANSYS Fluent Release 16.2 (3d, dp, pbns, lam, transient)

Simulation3 Particle File