Mechartés
SIMULATION EXPERTS

CFD Modeling in Cement Plants

Table of Contents

Introduction

Cement is primarily used in the manufacturing of concrete, which is a combination of inert mineral aggregates such as sand, gravel, crushed stones, and cement. Consumption and production of cement are directly connected to the building sector, and thus to the general economic activity. The cement industry is one of the main industries necessary for sustainable development. It can be considered the backbone of development and also be used as a parameter to see a nation's growth in terms of its production and consumption.

China produces the highest quantity of cement globally at an estimated 2.2 billion metric tons in 2020. China's cement production share equates to over half of the world's cement.

India was the world's second-largest cement producer in 2020, with production amounting to a distant 340 million metric tons. It accounts for more than 7% of the global installed capacity. Undoubtedly, these two nations are also the top two consumers of cement too. India and China have a lot of ongoing mega infrastructure projects and potential for further development in the infrastructure and construction sector and the cement sector is expected to largely benefit from it.

Working of a Cement Plant

- Cement is basically made by heating limestone (calcium carbonate) with small quantities of other materials to 1450+ ˚C in a kiln. The resultant hard material which is recovered after heating limestone and chemicals is called 'Clinker'.
- Clinker looks like small lumps. These lumps are crushed with a small amount of gypsum into a powdery form – which gives the final product.

Chemically, cement is a mixture of calcium silicates and small amounts of calcium aluminates that react with water and cause the cement to set. Calcium is derived from limestone and clay, mudstone or shale as the source of the silica and alumina. The mix is completed with the addition of 5% gypsum to help retard the setting time of the cement. So, in essence, the following components are compulsory for making OPC cement:

Limestone:

Found in natural reserves, extracted from mines. This is one big reason why so many cement plants are located near these mines. Then this limestone is crushed to -80 mm in size.

If the quality of limestone procured from mines is not of the correct quality, chemicals (correctives) have to be added to make Clinker of desired quality.

Alternate materials:

However, with time, people figured out that limestone can be substituted with other materials namely Fly ash or Slag, which will still provide the required strength but to a lesser extent.

Fly ash is a by-product of thermal power production. Most power producers want to dispose of fly ash, and one of the ways to do so is by selling it to cement manufacturers who can substitute it for limestone in the cement-making process. Similarly, slag is a by-product of the steelmaking process and is often sold to cement makers as a substitute for limestone.

Heat

Generally obtained from Coal, petcoke, or its variants. Raw limestone is transferred to a mill for grinding into a fine powder. This fine powder of limestone is then heated at a very high temperature of 1450 degrees centigrade for clinkerisation. To heat this fine powder at such a high temperature, coal is used in the clinkerisation section.

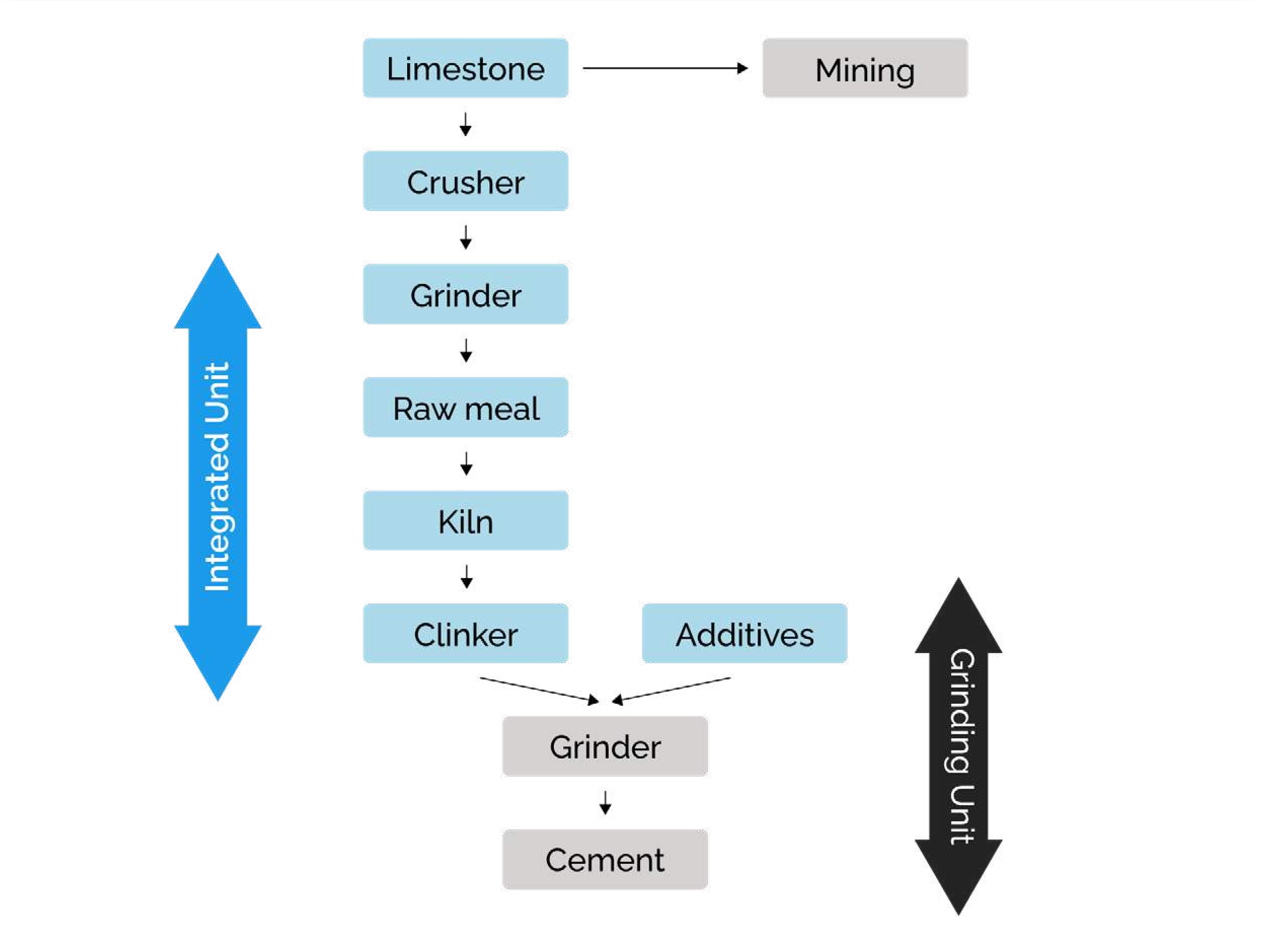
This clinkerised raw material is then fed into an electrostatic precipitator to store it in the form of the concrete silo. This is called kiln feed, which is fed into a preheater for pyro processing. Thus, heat is the next biggest requirement in the manufacturing process. Waste heat recovery is a mechanism that can lead to huge cost savings in terms of fuel cost.

The pyro processing of kiln feed produces cement clinkers. The hot clinkers are then cooled down and bucketed to store in clinker stockpiles.

Gypsum:

A mineral compulsory for providing the binding nature to cement. After the pyro processing stage, the clinker and gypsum are mixed together and sent to the mill inlet for the further grinding process to form a fine grey powder. This fine grey powder is the cement which is then packed and dispatched to the market for sale.

Cement Manufacturing Process



1. Mining / Extraction

Materials are extracted/quarried/recovered and transported to the cement plant.

2. Crushing and milling

The raw materials, limestone, shale, silica, and iron oxide are crushed and milled into fine powders.

3. Mixing and preheating

The powders are blended (raw meal) and preheated to around 900° C using the hot gases from the kiln. The preheating burns off the impurities.

4. Heating

Next, the material is burned in a large rotary kiln at 1500° C. Heating starts the de-carbonation where CO_2 is driven from the limestone. The partially fused result is known as clinker. A modern kiln can produce around 6000 tons of clinker a day.

$CaCO_3$ (limestone) + heat -> CaO (lime) + CO_2

5. Cooling and final grinding

The clinker is then cooled and ground to a fine powder in a tube or ball mill. A ball mill is a rotating drum filled with steel balls of different sizes (depending on the desired fineness of the cement) that crush and grind the clinker. Gypsum is added during the grinding process to provide means for controlling the setting of the cement.

The cement is bagged transported for concrete production.

Challenges in Cement Plants and the Role of CFD Simulations

Challenges in Cement Plants and the Role of CFD Simulations

Technology obsolescence has been one of the major reasons accounting for the industry's poor performance. Apart from the raw materials (quality of limestone or coal), some of the operational and day-to-day jobs that affect the overall production and profitability of a plant are

1. Reduced coal mill output
2. Increased grinding energy
3. Increased combustible loss
4. Increased fuel consumption
5. Difficult burning of clinker
6. More erosion
7. Improper & inefficient burning
8. Poor-quality clinker

The upgrading of existing cement plants or their equipment to current standards is a major challenge for the industry. This is generally due to the cost associated with it. Other factors include emission regulations and common physical and dimensional constraints of the existing equipment. Computational Fluid Dynamics analysis (CFD) can help deal with this problem because it makes it possible to perform several analyses at a lower cost and with great accuracy when compared to the traditional approaches.

Challenges in Cement Plants and the Role of CFD Simulations

Before implementing any design changes, analyze existing conditions within the facility with the help of specialized simulation experts like Mechartes.

The benefits of a CFD study are encouraging and are summarized below.

1. Increase in top-stage cyclone efficiency results in a reduction in exit temperature.

2. Uniform gas flow and material distribution.

3. Reduction in pressure drop across cyclones.

Mechartes is one such company with over 50 skilled engineers and simulation experts who work on root cause studies. They have helped several clients globally in the last 17 years by analyzing existing plant/site conditions to curate the best-fitted design modifications and techniques for their clients.

General Issues & Benefits of CFD in Different Stages of Cement Manufacturing Process

Baghouse analysis	Calciners/Pyroclone
Cyclones in preheater towers	
Kiln/clinker cooler simulation	
Burners	ESPs and Ducts

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

CFD has varied applications in a cement plant from optimizing the process design to the overall operation. Typical problems within the system are potential regions of high-pressure drop, high velocity, recirculation regions, wear, and tear/erosion, heat loss. For e.g.:

I. Baghouse analysis

Baghouse filters are widely used for the control of emissions of particulate matter in industries and have high efficiency, generally above 99%, for fumes and dust above 0.1µm. They are a very complex installation and operation equipment. A good performance of a baghouse filter is closely linked to the correct flow distribution inside it, whether in the hopper or in the bags. Other important variables for good performance are internal speed, filtration rate (RAP), pressure drop, cleaning efficiency, etc.

II. Calciners/Pyroclone

CFD analysis of Pyroclone to increase the retention time for coal combustion, plant capacity and to minimize the unburnt coal particles.

All modern cement industries have installed pyroclone before rotary kiln. The calcination reaction, which is an endothermic reaction, is generally performed in the pyroclone. Therefore, the heat required for the reaction is provided by the burning of petcoke. Generally, 90-95% of the calcination is achieved here.

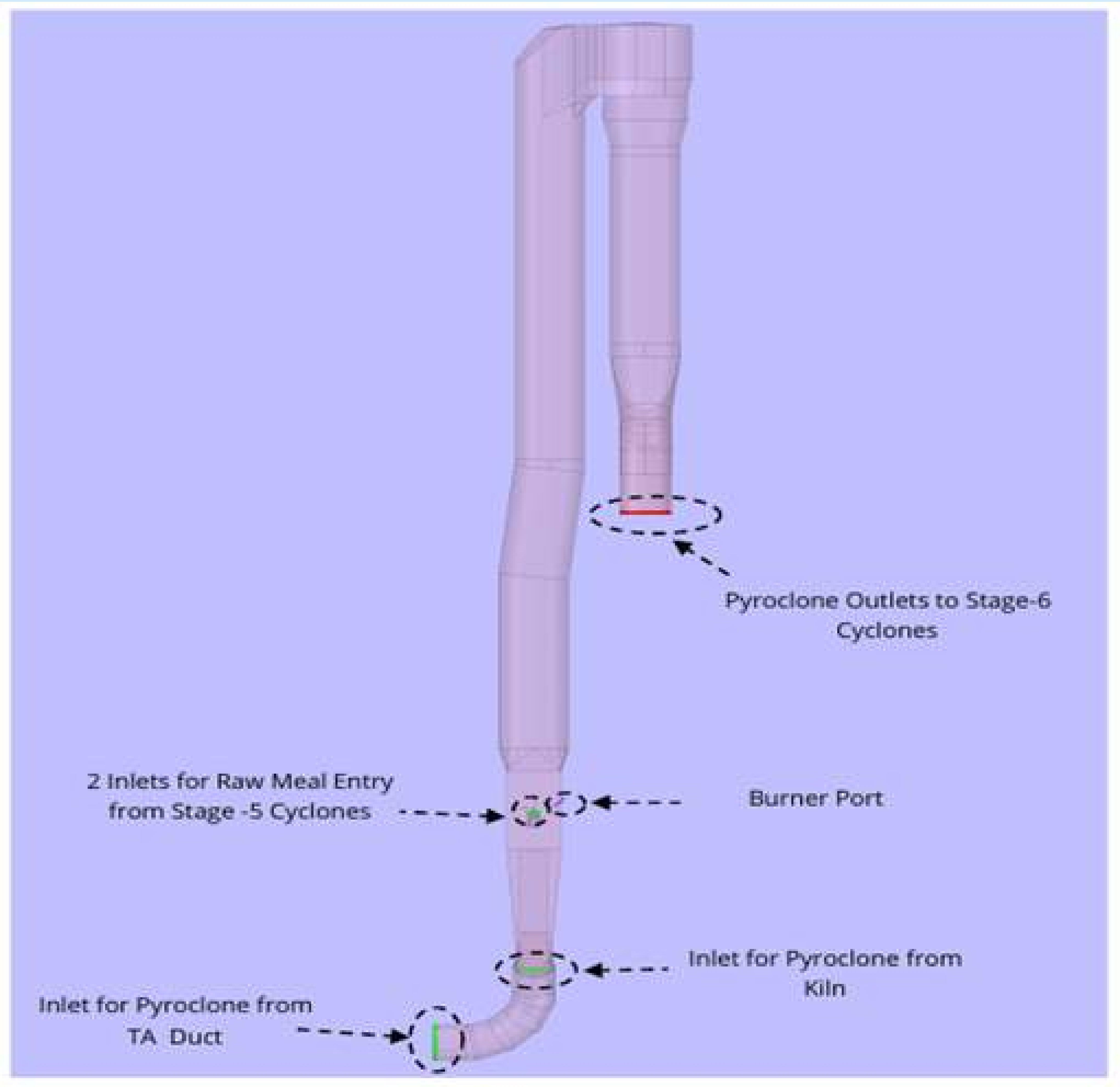
Separate preheating of feed and calcination before the rotary kiln helps to improve the thermal efficiency of the plant and hold out the prospects of the nearly total elimination of heat wastage from rotary kilns. This allows for an increased throughput for a given-sized rotary kiln tube and the production of higher-quality cement.

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

One can easily identify the percentage combustion of petcoke at the outlet of pyroclone and provide recommendations to achieve 100% combustion inside the pyroclone. Therefore, the heat released by the combustion can be used to achieve the maximum percentage of calcination. Thereby, reducing the energy demand and thermal load on Rotary Kiln, so that overall energy consumption can be minimized to improve the plant efficiency.

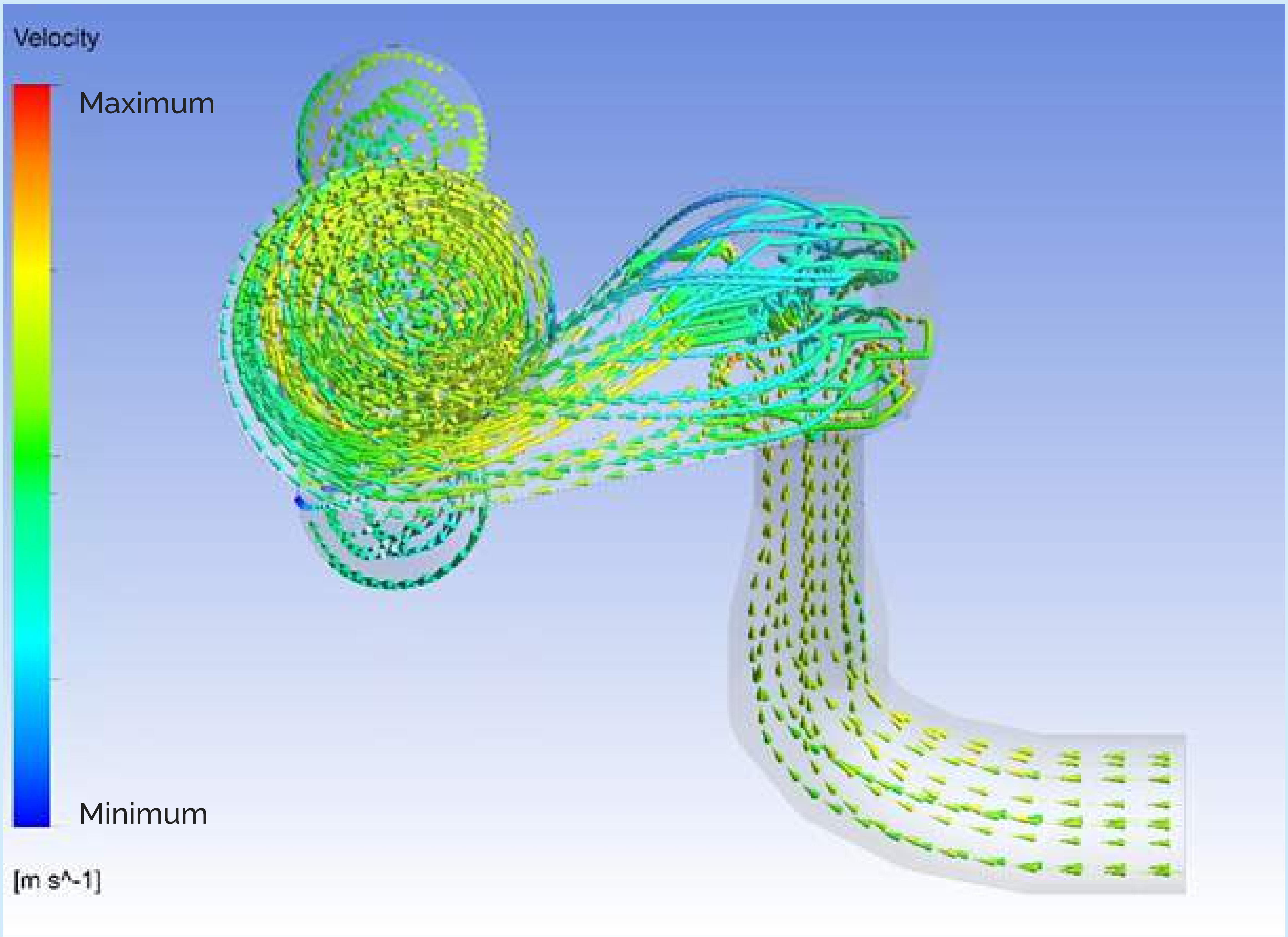
However, as a general principle the high fineness of raw material and good turbulent mixing causes uniform and fast coal combustion and calcination reaction. Therefore, understanding the mechanism of flow and transport phenomena in the pyroclone is important for efficient cement production.

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process



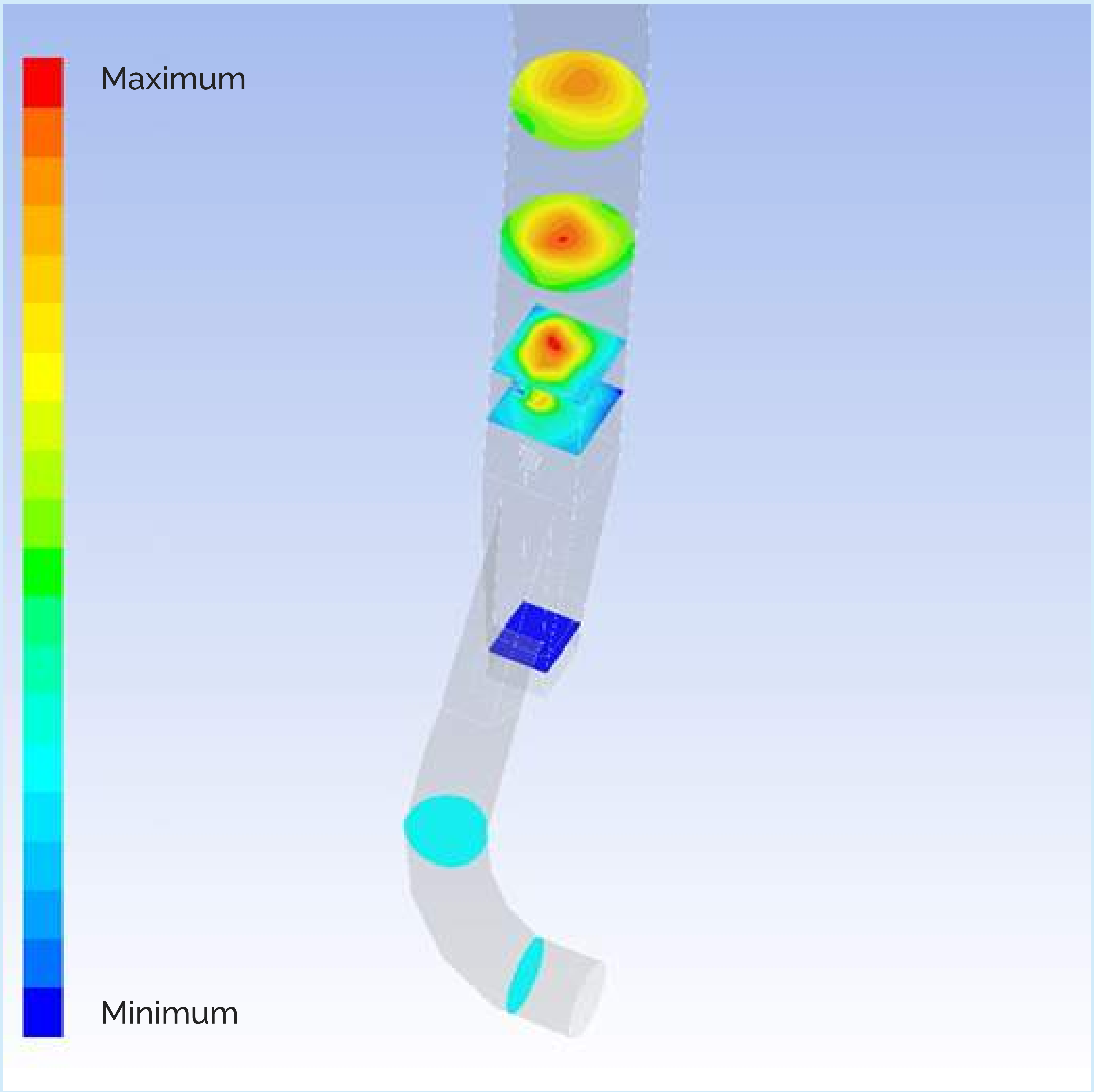
3D Model of Pyroclone

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process



Velocity path lines in a zoomed top view of “Pyroclone” for **Case -1**

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process



Contour plot of CO_2 (in mass fraction) at different heights in section -1 (zoomed view) of "Pyroclone"

III. Cyclones in preheater towers

In modern Cement industries, the raw material consist of pulverized Calcium carbonate ($CaCO_3$) is preheated and moisture is evaporated in a multi-stage cyclones counter currently with the hot flue gases (coming form the rotary kiln and tertiary duct) before entering the pyroclone . The raw material undergoes a calcination reaction to form Calcium oxide (CaO) and Carbon dioxide (CO_2), as shown in below equation, which is a endothermic reaction.

$$CaCO_3 \xrightarrow{1160K} CaO + CO_2 \qquad +178 KJ/mol$$

Therefore, the heat required for the reaction is provided by the combustion of pulverized petcoke and the raw material undergoes 80-90% calcination. Based on the proximate and ultimate analysis of petcoke, a two-stage combustion phenomenon is implemented, In the first reaction, it produces Carbon monoxide (CO) and in the second reaction, it is converted into Carbon dioxide (CO_2).

The following governing equations for combustion are shown in the equation-(3.9 - 3.10). The products from pyroclone are fed to the last cyclone which feeds the rotary kiln. The reaction chemistry for combustion and calcination is implemented in the Ansys Fluent CFD software. All the species undergoing Physico-chemical changes in this modeling are conserved by solving the species transport equation along with the particle surface reaction. The general species transport equation is shown below:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot \rho Y_i u = \nabla \cdot \rho D_i \nabla Y_i + \dot{m}_i'''$$

Where, u is a velocity vector , Y_i is mass fraction of a chemical species i and m is the mass source for chemical species i due to chemical reaction, which may be generating or depleting.

$$C_{0.11}H_{8.17}O_{0.17}N_{0.2745}S_{0.4282} + 2.44O_2 \rightarrow$$
$$0.11CO + 4.08H_2O + 0.1372N_2 + 0.4282SO_2$$

$$CO + 0.5O_2 \rightarrow CO_2$$

However, As a general principle the high fineness of raw material and good turbulent mixing causes uniform and fast coal combustion and calcination reaction. Therefore, understanding the mechanism of flow and transport phenomena in the pyroclone is important for efficient cement production.

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

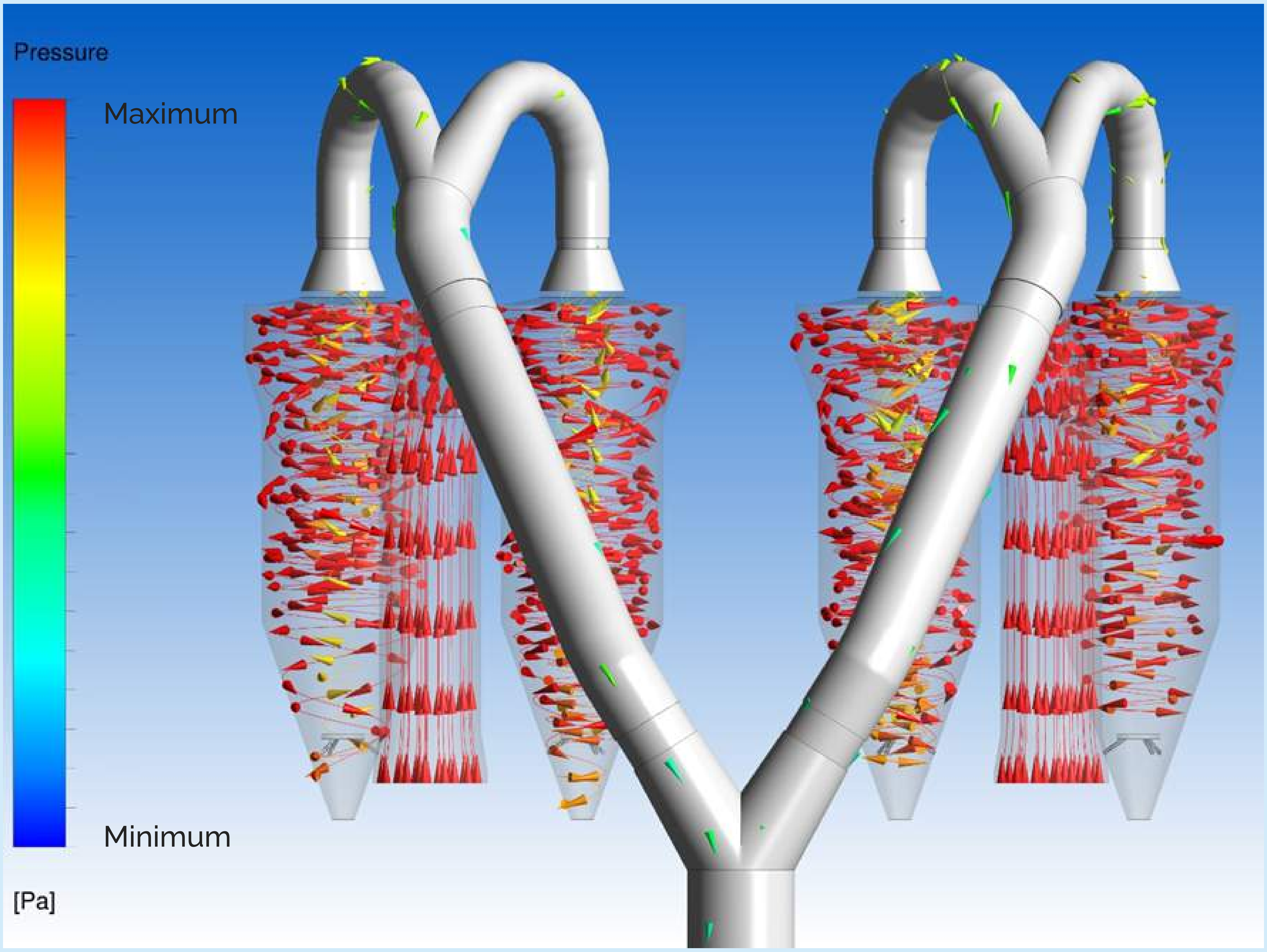


Fig.: Pressure pathlines of stage-2 cyclone outlets to stage-1 cyclone outlets with Down Comer Duct

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

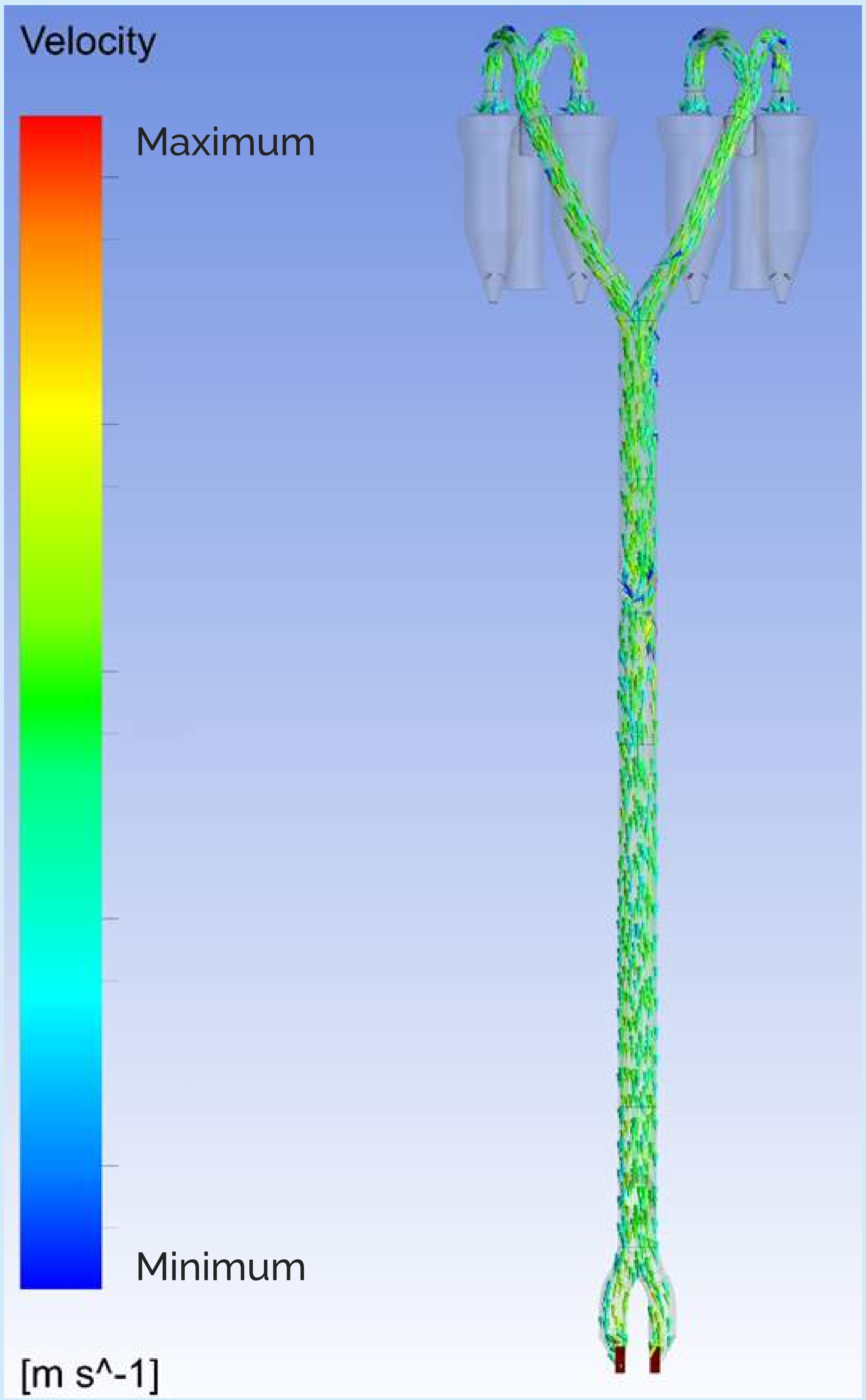


Fig.: Velocity pathlines of stage-1 cyclone outlets to PH fan inlets of Cyclones with Down Comer Duct

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SIMULATION EXPERTS

IV. Kiln/clinker cooler simulation

The working principle of the clinker cooler used in the cement plants are to reduce the clinker temperature by using the combination of recirculated waste heat air & ambient air introduced at bottom of the grate coolers which travels through the clinker bed.

Due to the heat transfer mechanism between clinker material and air introduced below the grate coolers, the clinker material gradually cools to 100-200 oC and leaves from the other end of the cooler. The hot gases leaving from the clinker bed in the cooler are diverted to the tertiary air duct and kiln at the entrance of the cooler and to the WHR boiler at mid of the cooler section or to the ESP at end of the cooler section.

Sometimes it is observed at a site that a substantial amount of fine clinker dust particles gets carried over into the tertiary air duct along with hot gases. So, to minimize the clinker dust particles' carryover into the tertiary air duct by reducing the flue gas velocity in the kiln hood, design modifications using the CFD model can be used.

It helps to study the flow profiles & dust particle movement for the existing kiln hood and also for modified kiln hood along with possible further improvements to minimize the clinker dust particle carryover into the tertiary air duct.

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

It is important to simulate the turbulence behavior of the flow with the help of turbulence models. In this work, the RANS-based turbulence model of the realizable k-ε turbulence model was used for simulating the turbulence behavior of the flow. Choosing the right equation model and as per the site requirement is equally critical and shows how experienced and well versed are CFD consultant's

CFD analysis of the kiln hood can help minimize the escape of dust particles into the tertiary duct to minimize the pressure drop in clinker coolers and to improve the flow profiles.

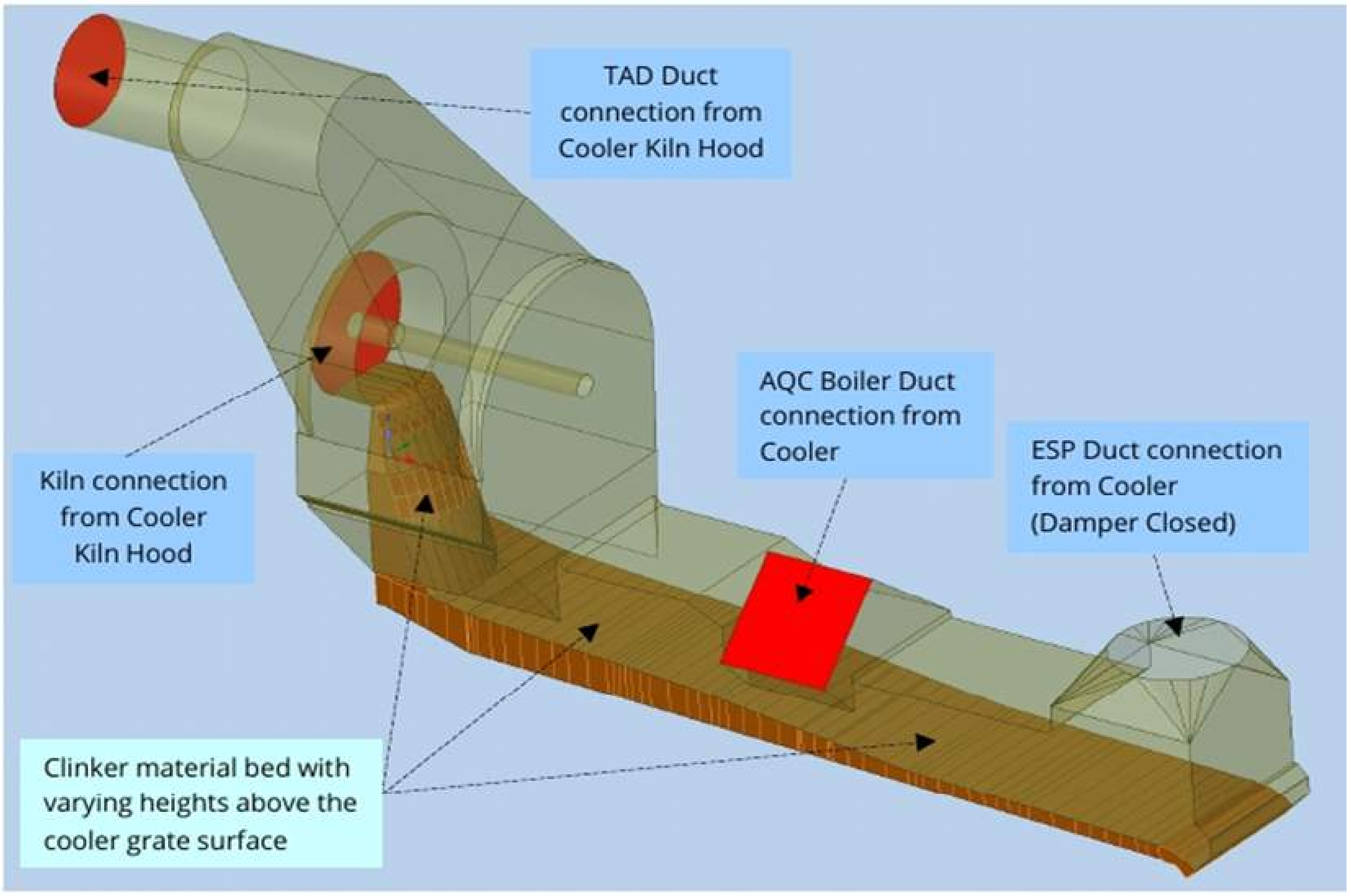
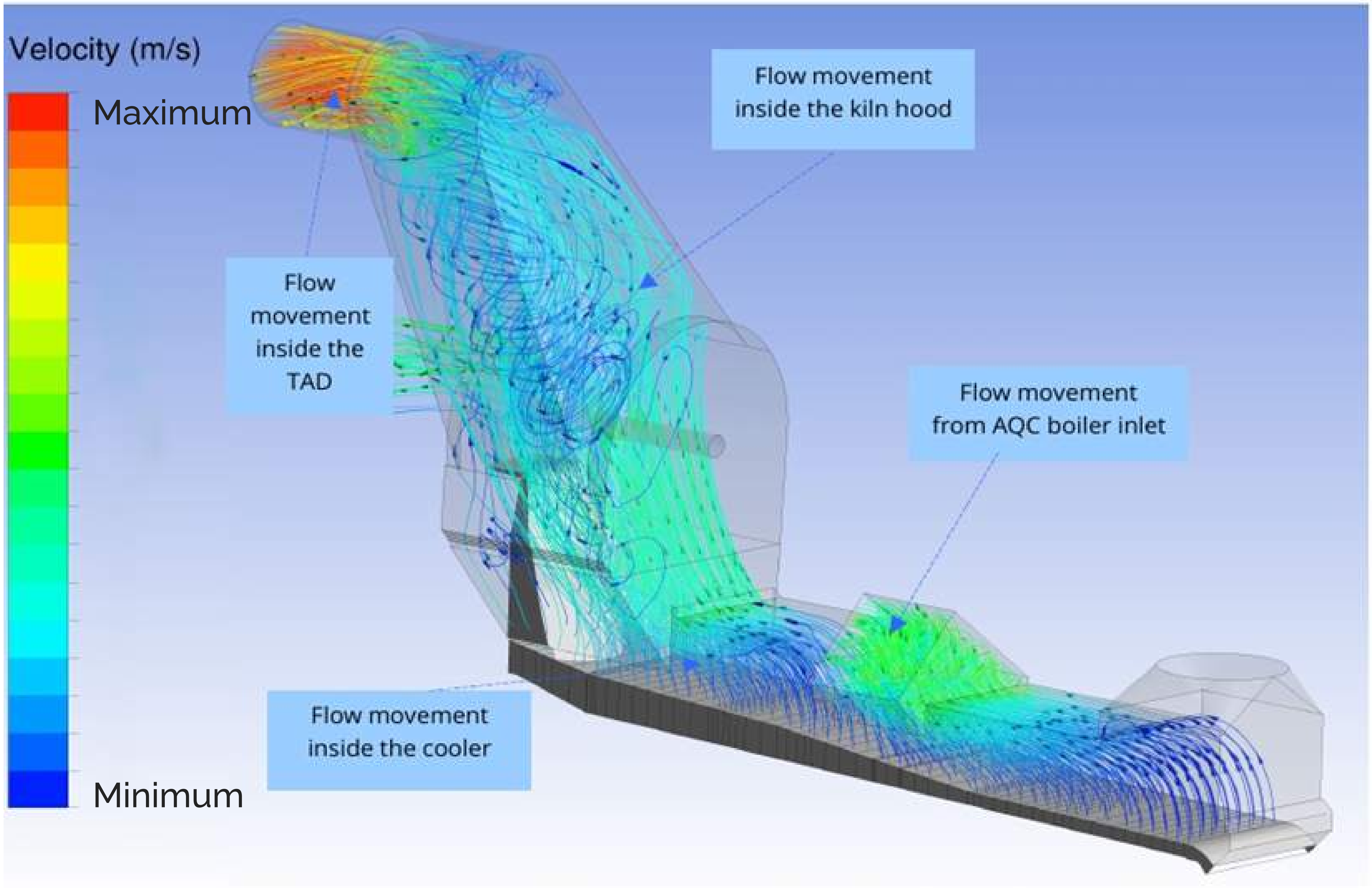


Fig. After preparing the 3d model of the geometry, hexahedral and tetrahedral mesh with mesh sizes of 0.0001m to 0.15m were created and total mesh cells of around 5.5 million were obtained.

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process



V. Burners

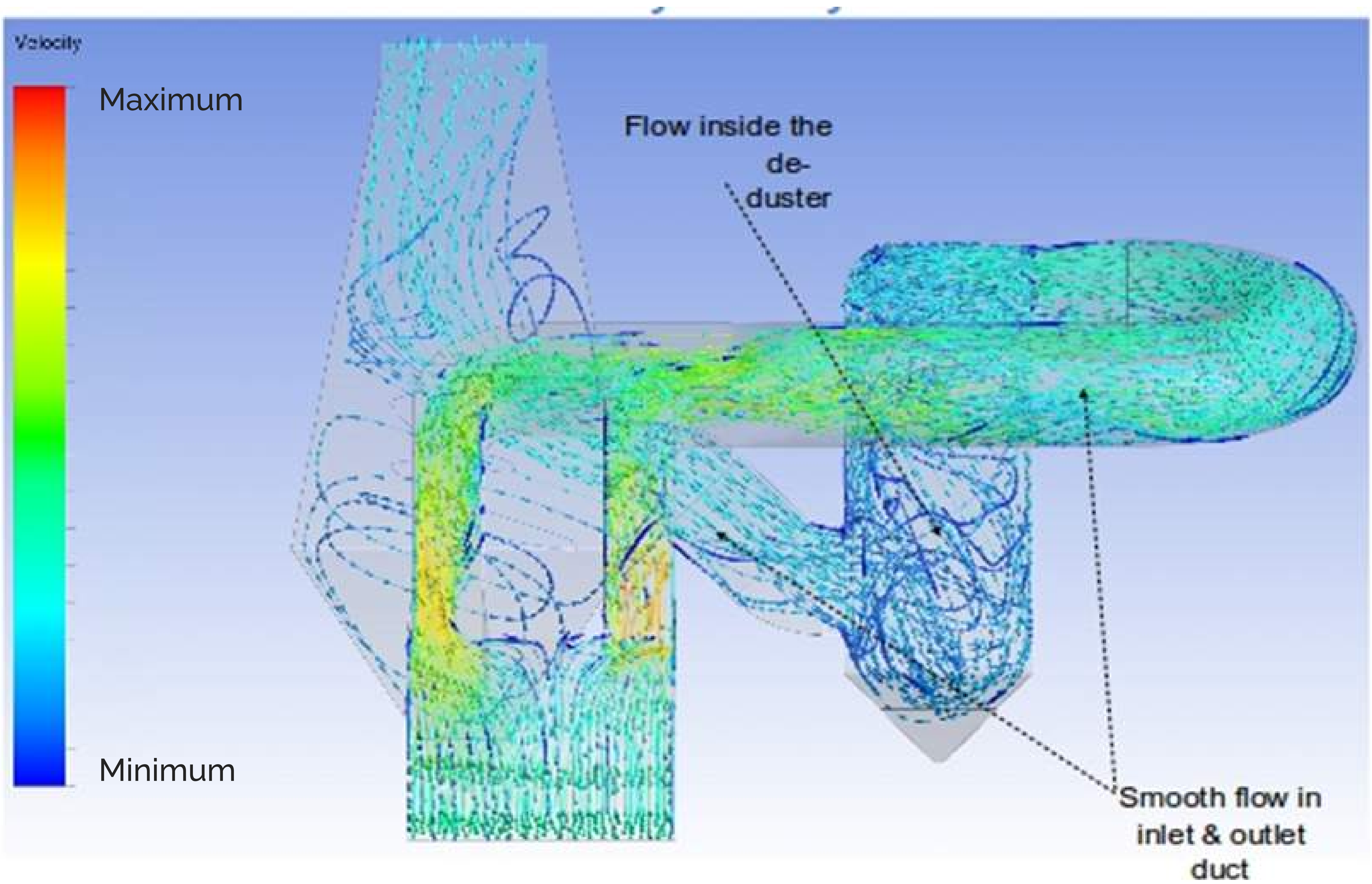
CFD analysis can also be used to study between clinker cooler and AQC boilers to capture the max percentage of clinker dust particles in the de-duster to minimize the erosion in the boiler ducts. To understand the Flue gas flow and the dust flow inside the boiler or evaporator tube banks and to find the root cause of erosion, CFD is the only answer.

VI. ESPs and Ducts

Proper flow through an ESP is critical for optimal performance. Improper flow can result in unwanted dust build-up and erosion. CFD analysis can be used to study ducts, including their cyclones to reduce the pressure drop and improve the flow profiles. CFD can also be used to study the flue gas flow and dust flow behaviour, which can give important insights to causes of erosion happening in ducts, and ways to rectify it without affecting the pressure drop.

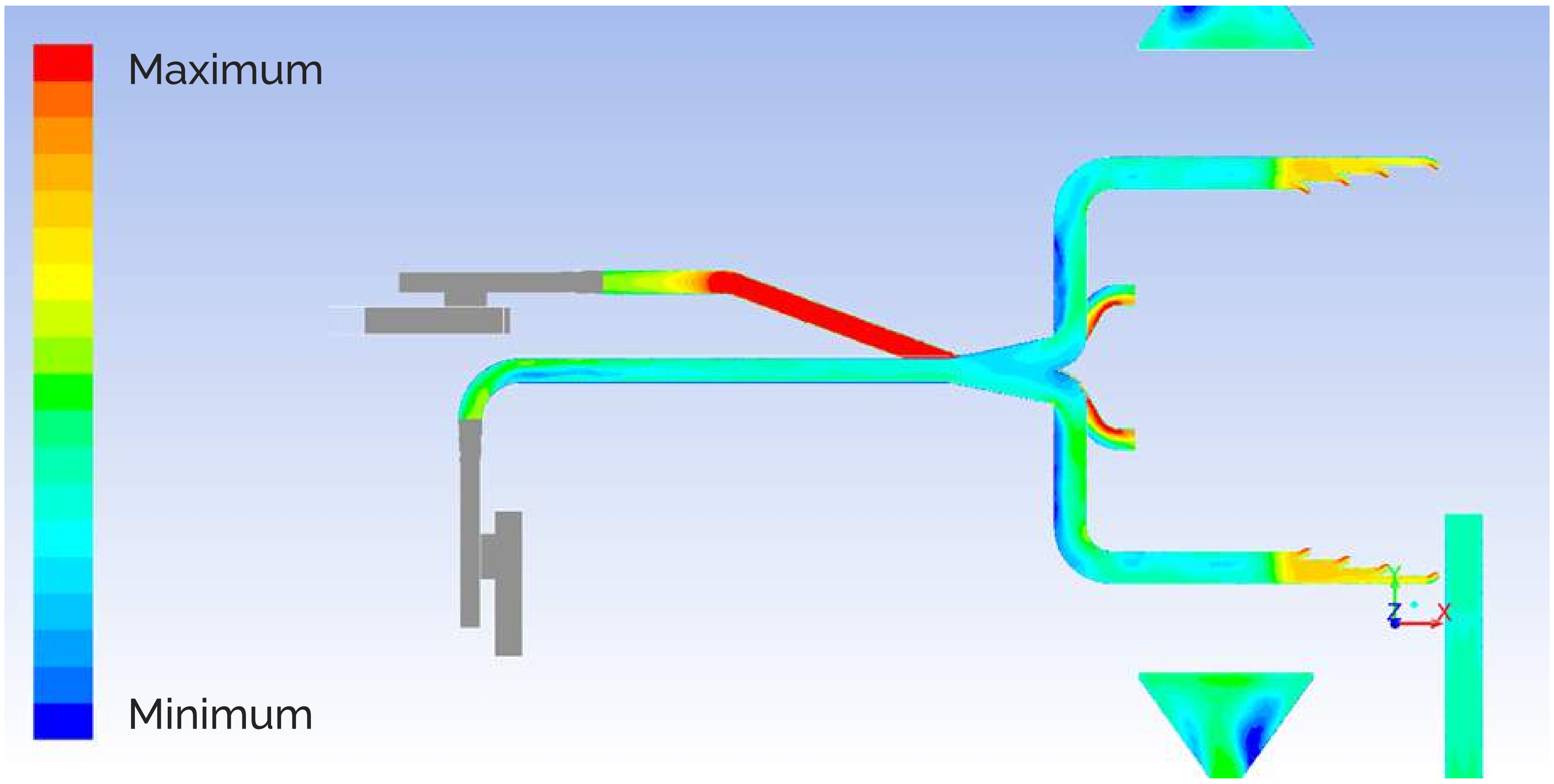
General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

Improving the fluid flow distribution through ducts and other connected equipment (ID fans, ESP fan outlet), can increase efficiency and eliminate persistent maintenance costs. Due to poor design, ducts may suffer from low efficiency due to gas/air/dust recirculation, flow separation, and high turbulence intensity.

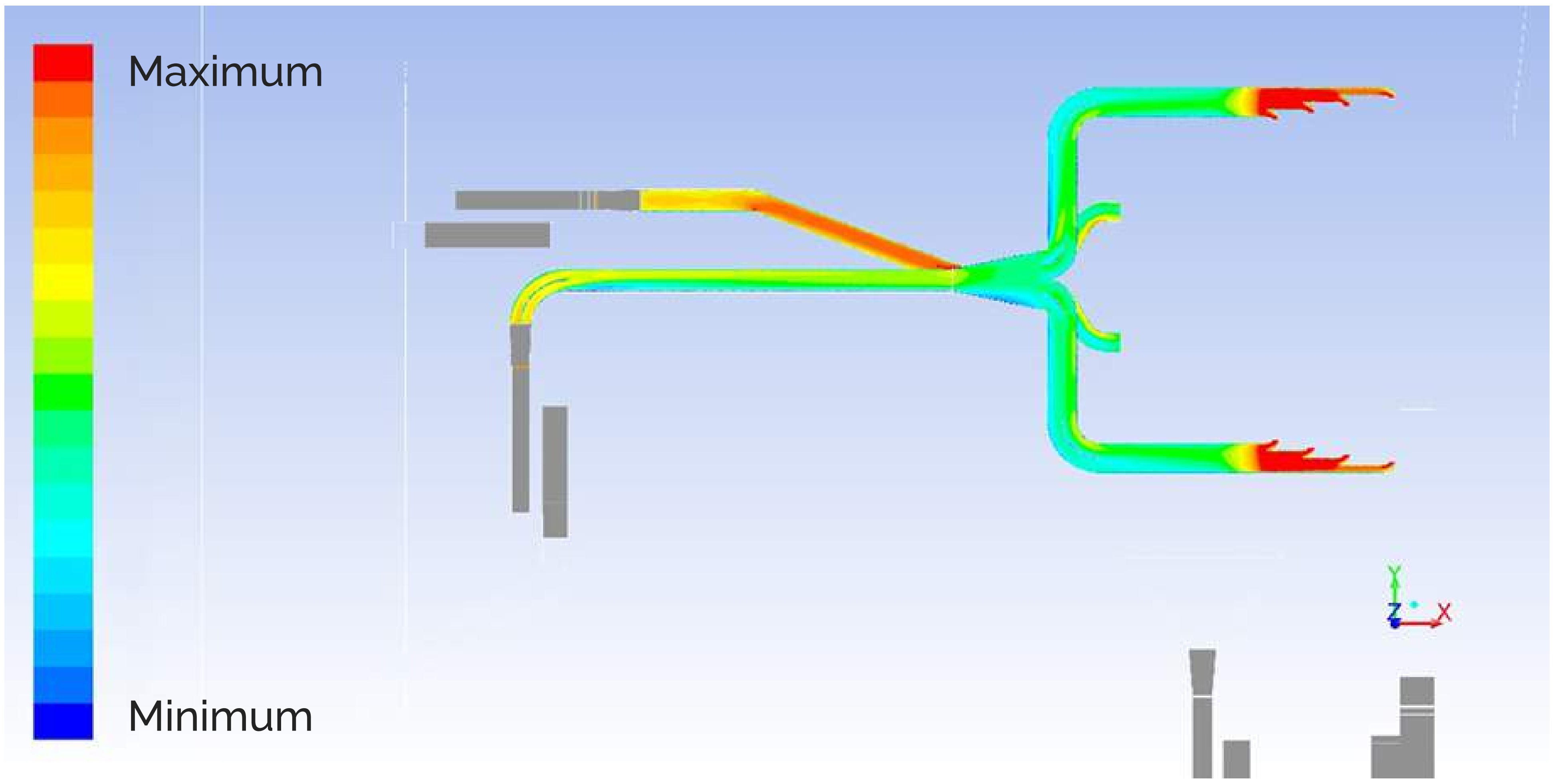


Unequal velocity is observed at the outlet duct connections of fan-4

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process



Unequal velocity being observed at the outlet duct connections of fan-4



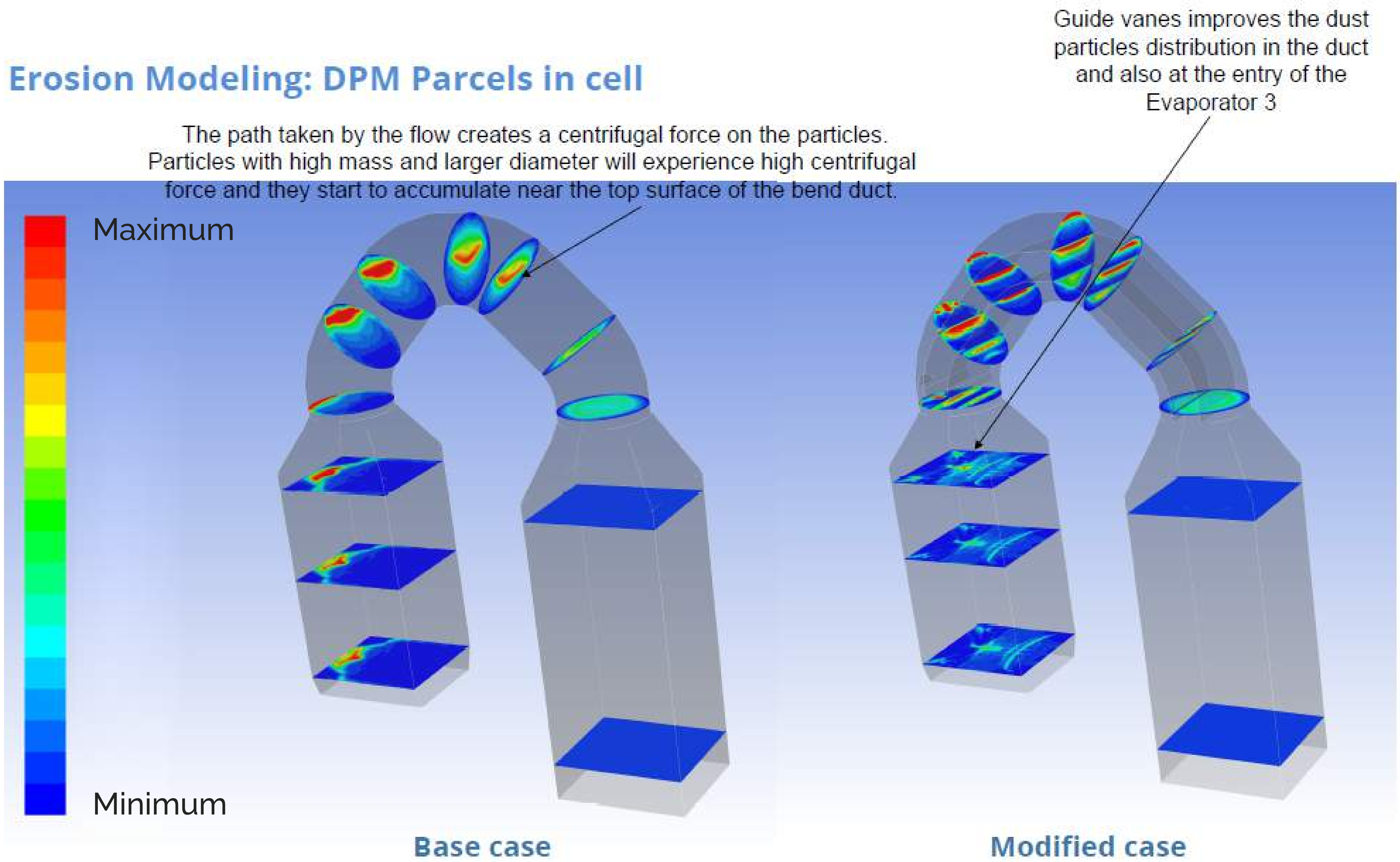
Guide vanes are guiding the flow inside the outlet duct connections of fan-4 properly, which resulted in proper distributions of the velocities

General Issues & Benefits of CFD in Different Stages of Cement Mfg. Process

CFD Result: After design modifications based on preliminary CFD analysis.

CFD simulations provided the information and insight to the duct designer to optimize the system design before implementing the modifications.

The key benefit of CFD is it saves Time and Money as it is "Simulation-Based Design" instead of "Build and Test".



Steps in CFD in Cement Plants

Time Required to Implement CFD

Time required to complete a CFD study by a CFD consultant depends upon the size and complexity of the problem, and it can vary between 4 to 16 weeks. However, the cement plant requires a few days of shutdown for implementing the project. The major steps involved include:

1. Site Visit and data collection and verification. Verified Data can also be provided by the Cement plant owners/mgmt., so site visits and data collection by the CFD consultant party can be avoided and time can be saved.

2. Phase 1: Identifying the problem/cause:

- Defining the geometry and domain
- 3D Model generation
- Mesh generation – Mesh selection depends on the application. For a 3D application, there are tetrahedrons, hexahedrons, prisms, pyramids, polyhedrons. Selection should consider the mesh generation/setup time, the computational time required to obtain the solution, and the selection of governing equations.

- Specifying boundary conditions, such as the Navier Stokes (NS) equations, conservation of mass & momentum, and energy models as applicable to the simulation.
- Monitoring the iterative solution process
- Post Processing/Validation
- CFD Report/Recommendation - CFD results like velocity, temperature, flow pattern, and temperature profiles are presented based on the initial boundary conditions.

3. Phase 2: Rectify the problem with Design Modifications as per Phase 1 CFD analysis results and site constraints:

- 3D Model modifications based on CFD results
- Mesh generation
- Specifying boundary conditions
- Monitoring the iterative solution process
- Post Processing/ Validation
- CFD Report/Recommendation - CFD results like velocity, temperature, flow pattern, and temperature profiles are presented based on the modified boundary conditions.

Steps in CFD in Cement Plants

Whether it is a Cement Mill, Raw Mill, Coal Mill, or Cooler equipment, Mechartes has decent expertise in providing CFD modeling, and with our experience in various similar projects, we can give the right suggestions to achieve the desired output/performance. The improved case design modifications can be provided with GA & fabrication drawing as well.

Before you pick any CFD consultant: How can you make sure it does not only produce colorful images/reports for you but the real value for your problem/plant?

To sum up, the accuracy and trustworthiness of the simulation rely on the CFD consultant who has to translate the real-plant objective into the 3D Model, consisting of the right CFD tool (in our case it is ANSYS Fluent/CFX, OpenFOAM), the right model and the right problem-solving approach with right interpretation and suggestions of the colorful images which we get as an output.

About Mechartes Services in Cement/ Process Plants

About Mechartes Services in Cement/ Process Plants

We at Mechatres are focussed on providing accurate simulation results with a professional engineering approach. Our simulations represent the system closely and physics correctly at each parameter and step. With expertise in advanced numerical tools like Computational Fluid Dynamics (CFD) and Finite Element Method (FEM), we offer the following services in the Cement Industry/Process sector:

- CFD Modeling
- Multiphase flow analysis including recirculation, particle trajectory study
- Erosion Analysis
- Separation Analysis
- Mixing Process Analysis
- Design Optimization of Downcomer and Cyclone Inlet Ducts
- Design Verification and Validation of De-duster, ESP, Silo
- Piping Stress & Support design
- Surge and Slug Analysis
- Boiler Analysis

You can find more case studies and other resources at our website.

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