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CFD SIMULATION OF FLUE GAS DUCTING IN WASTE HEAT RECOVERY PLANT

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ABSTRACT
In the highly competitive metal production and power generation industries, the difference between energy recovered and energy wasted often determines the difference between profit and loss. A waste heat boiler is one of the devices generally employed to recover energy from high temperature furnace gases, extracting a significant fraction of waste energy. Waste Heat Recovery Boiler (WHRB) is the quintessential example of energy optimization in this age of renewal and energy saving. They capture the waste heat from the process systems and utilize it for other heating process, which ultimately increase the efficiency of plant. However, working stage of WHRB is challenging as design is prepared depending on site constraints and it is expected to deliver high efficiency even when dealing with high velocity and high temperature flows. CFD is widely used to investigate the flow pattern, pressure drop across ducting and particle trajectory within various equipment. CFD can be used to address problems with existing geometrical or performance errors like erosion of duct material due to ash particles, flow non-uniformity at tube bundles entry. Such problems may lead to lower efficiency of the equipment. Therefore, CFD can provide insight in the behavior of the system and contribute to resolving the problem. CFD has helped in improving the flow pattern by arrangement of baffles, flow separators at required locations within prescribed pressure drop across system, improving particle separation efficiency. In this works CFD is used to analyze & improve flow distribution inside the WHRS, which enhance the Thermal efficiency of the boiler, proper distribution of particles to avoid erosion of the tubes and optimization in the pressure drop in WHRS The geometry and mesh was created in Hypermesh & T-grid. The analysis was conducted using advanced CFD software tool, Fluent. Fluent has been applied extensively worldwide for different engineering applications. Fluent solves numerically the Navier-Stokes equations (the fundamental fluid dynamics governing equations). The discrete phase modelling is done by DPM Multiphase approach.

I. INTRODUCTION
Nowadays, extending the energy supply, design optimization and increasing the efficiency are the main goals and targets of the industries and their future plans. Due to the increase of human population, a continuously increasing amount of electricity needs to be generated. There are various technologies for power generation in the world, such as wind energy, water energy, steam turbines and gas turbines. In this regard, steam is used as the main source of energy for processes, heating, chemical reactions, power generation, etc. in most industries. On the other hand, the costs of the fuels are increasing continuously in the entire world. Consequently development of new methods for electricity and power generation, increasing efficiency and also cost optimization of power plants are attractive subjects for engineers. Some part of the world's power is generated in thermal power plants by using fired boilers and steam turbines. Also, any probable emissions of NOx, SOx and CO could be reduced in the process of heat recovery. Considering the wide range of the exhaust gas temperature and relevant specifications, heat recovery steam generators play a very important role in the cement plants. Therefore, the terms waste heat boiler and heat recovery boiler are considered synonyms. The cement industry has a significant environmental footprint due to the extensive amounts of energy and raw materials used in the process. Consequently, cement manufacture releases a great deal of carbon dioxide (CO_2). In fact, cement production is responsible for about five percent of total global CO_2 emissions. Typically, 40 percent of direct CO_2 emissions comes from combusting fuel required to drive the reactions necessary to make clinker; 60 percent comes from the de-carbonation reaction itself. Approaches include installing more fuel-efficient kilns, using less carbon-intensive fuels in the kiln, partial substitution of noncarbonated sources of CaO in

the kiln raw materials, installation of heat recovery boilers and partial substitution of supplementary cementitious materials (SCM) such as blast furnace slag, fly ash and limestone for OPC in finished cement products

Known energy sources exhausted from cement industries. Effective utilization of these sources is required in order to improve the efficiency of the plant. Preheater boiler and Air quench cooling (AQC) boiler is designed in order to recover the waste heat from the exhaust gases. The detail boiler design is carried out considering the various limitations to produce the superheated steam at higher temperature from the waste heat recovery boilers. The exhaust gas temperature is limited above the acid dew point temperature to avoid the corrosion problems over the tubes.

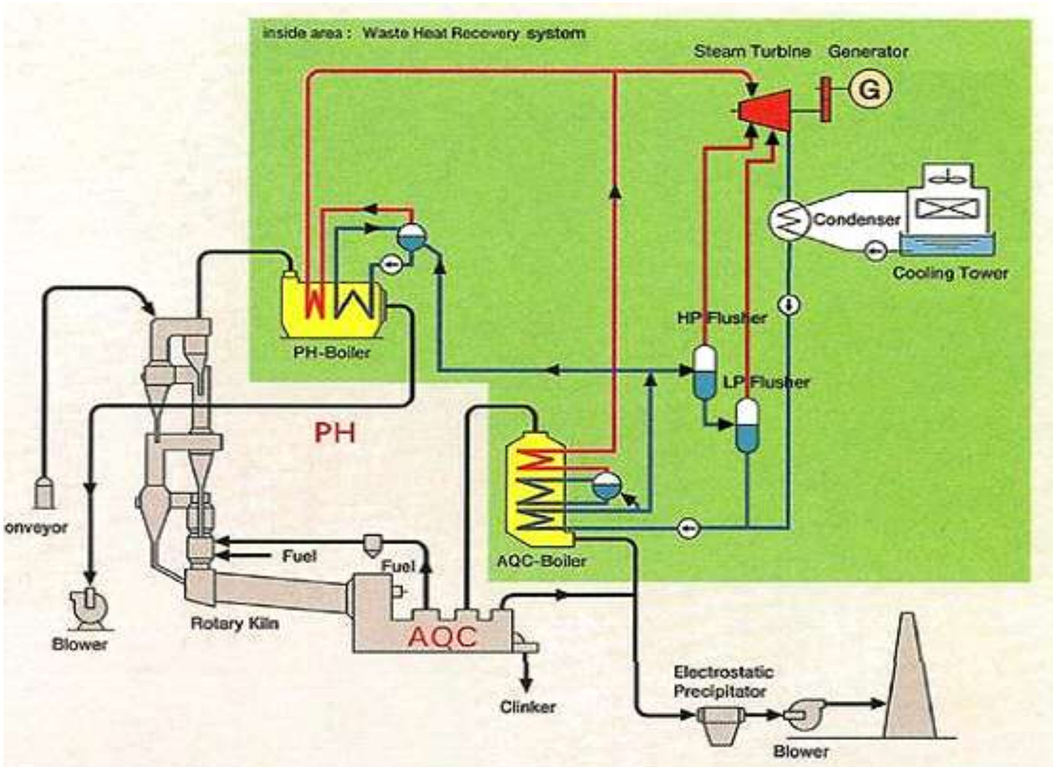
Waste Heat Recovery Power Systems

State-of-the-art new suspension process kilns include multi-stage preheaters and pre-calciners to pre-process raw materials before they enter the kiln, and an air-quench system to cool the clinker product. Kiln exhaust streams, from the clinker cooler and the kiln pre heater system, contain useful thermal energy that can be converted into power. Typically, the clinker coolers release large amounts of heated air at 250 to 340° C (480 to 645° F) directly into the atmosphere. At the kiln charging side, the 300 to 400° C (570 to 750° F) kiln gas coming off the pre heaters is typically used to dry material in the raw mill and/or the coal mill and then sent to electrostatic precipitators or bag filter houses to remove dust before finally being vented to the atmosphere. If the raw mill is down, the exhaust gas would be cooled with a water spray or cold air before it entered the dust collectors. Maximizing overall kiln process efficiency is paramount for efficient plant operation, but remaining waste heat from the preheater exhausts and clinker coolers can be recovered and used to provide low temperature heating needs in the plant, or used to generate power to offset a portion of power purchased from the grid, or captive power generated by fuel consumption at the site. Typically, cement plants do not have significant low-temperature heating requirements, so most waste heat recovery projects have been for power generation. The amount of waste heat available for recovery depends on kiln system design and production, the moisture content of the raw materials, and the amount of heat required for drying in the raw mill system, solid fuel system and cement mill.

Waste heat recovery can provide up to 30 percent of a cement plant's overall electricity needs and offers the following advantages:

- Reduces purchased power consumption (or reduces reliance on captive power plants), which in turn reduces operating costs.
- Mitigates the impact of future electric price increases
- Enhances plant power reliability
- Improves plant competitive position in the market
- Lowers plant specific energy consumption, reducing greenhouse gas emissions (based on credit for reduced central station power generation or reduced fossil-fired captive power generation at the cement plant)

Waste heat recovery power systems used for cement kilns operate on the Rankine Cycle. This thermodynamic cycle is the basis for conventional thermal power generating stations and consists of a heat source (boiler) that converts a liquid working fluid to high-pressure vapour (steam, in a power station) that is then expanded through a turbo generator producing power. Low-pressure vapour exhausted from the turbo generator is condensed back to a liquid state, with condensate from the condenser returned to the boiler feed water pump to continue the cycle. Waste heat recovery systems consist of heat exchangers or heat recovery steam generators (HRSGs) that transfer heat from the exhaust gases to the working fluid inside, turbines, electric generators, condensers, and a working fluid cooling system. The most commonly used Rankine cycle system for waste heat recovery power generation uses water as the working fluid and involves generating steam in a waste heat boiler, which then drives a steam turbine. Steam turbines are one of the oldest and most versatile power generation technologies in use. As shown in Figure 1.1, in the steam waste heat recovery steam cycle, the working fluid—water—is first pumped to elevated pressure before entering a waste heat recovery boiler. The water is vaporized into high-pressure steam by the hot exhaust from the process and then expanded to lower temperature and pressure in a turbine, generating mechanical power that drives an electric generator. The low-pressure steam is then exhausted to a condenser at vacuum conditions, where the expanded vapour is condensed to low-pressure liquid and returned to the feed water pump and boiler. Steam cycles are by far the most common waste heat recovery systems in operation in cement plants, and generally reflect the following



II. THEORY & DESCREPTION

Mass conservation equations

According to the mass conservation, the rate of the mass increase in fluid element is equal to the net rate of the flow into the fluid element. For the compressible flow this can be formulated as follows and is called the continuity equation for an unsteady compressible fluid at a point:

$$\frac{\partial \rho}{\partial t} + div(\rho \cdot \vec{u}) = 0$$

The first term is the rate of the density change per time and the second term is called the convective term and is the net mass flow crosswise the boundaries

Momentum conservation equations

According to the second law of Newton the net forces on a fluid particle is equal to the net momentum change of the particle. There are two kinds of forces on a fluid particle; body forces such as gravity or Coriolis or centrifugal and surface forces such as pressure or viscous forces.

The momentum equation in the x direction:

$$\rho \frac{Du}{Dt} = \frac{\partial(-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

The momentum equation in the y direction:

$$\rho \frac{Dv}{Dt} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(-p + \tau_{yy})}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{My}$$

The momentum equation in the z direction:

$$\rho \frac{Dw}{Dt} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial(-p + \tau_{zz})}{\partial z} + S_{Mz}$$

The SM terms are the representative of the body forces and u, v and w are the velocity components.

Energy conservation equation
According to the law of thermodynamics the energy change rate for a fluid particle is the rate of work done on the fluid particle in addition to the heat added.

$$\rho \frac{DE}{Dt} = -div(p\vec{u}) + \begin{bmatrix} \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \\ + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y} + \frac{\partial(v\tau_{zy})}{\partial z} + \\ + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z} \end{bmatrix} + div(k \cdot gradT) + S_E$$

$$E = i + \frac{1}{2}(u^2 + v^2 + w^2)$$

The term E consists of internal energy i and the kinetic energy. The SE term is the energy term related to a source. The term including the temperature gradient is the heat transfer to the fluid and the rest terms of the right side are the work done on the fluid particle.

When gas flows in the channel the governing equations consist of continuity, momentum and energy equation. And the times averaged of those equations are as follows (in Cartesian):
Continuity equation:

$$\frac{\partial U_i}{\partial x_i} = 0$$

Momentum equation:

$$\rho \frac{\partial U_i}{\partial t} + \rho U_j \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\rho \overline{u'_i u'_j}\right) - \rho g_i \beta \Delta\Theta$$

Energy equation

$$\rho c_p \frac{\partial \Theta}{\partial t} + \rho c_p U_j \frac{\partial \Theta}{\partial x_j} = \lambda \frac{\partial^2 \Theta}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j}\left(-\rho c_p \overline{u'_j \theta}\right) + Q$$

For solving these equations containing Reynolds stress $\overline{u'_i u'_j}$ terms and turbulence heat flux $\overline{u'_j \theta}$, turbulence models are used. In our case since it is isothermal, the terms consisting ΔΘ disappear, i.e. the last term in momentum equation and the whole energy equation.

Navier Stokes equations
In order to close and solve the equations, the viscous stresses of τij must be modeled and this can be done in the Newtonian fluids by the linear relation of the rate of the deformation to the viscous stresses. And the relation coefficient is μ, i.e. the dynamic viscosity for relating the linear deformations to stresses and λ, i.e. the second viscosity to relate the volumetric deformations to stresses. In result the three dimensional tensor of viscous stress can be gained:

This is a statement of the principle of mass conservation for a steady, one-dimensional flow, with one inlet and one outlet.

$$\Delta (\rho V) + \partial\rho / \partial t = 0$$

$$\partial\rho / \partial t + \partial(\rho.u) / \partial x + \partial(\rho.v) / \partial y + \partial(\rho.w) / \partial z = 0$$

There are thus three different momentum equations that together comprise the Navier-Stokes Equations.

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$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial x}+\rho g_x+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial P}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial P}{\partial z}+\rho g_z+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

This expression of the energy equation is valid for most applications

Continuous Phase:

Analysis was carried out considering inputs

- Operating pressure : 101325 Pa
- Mass Flow at Inlet : 53.7 kg/s (=150000 Nm^3/hr/3600*1.2879 kg/Nm^3)
- Static Pressure at Outlet : 0 Pa
- Temperature : 703.15K
- Wall : No-slip wall

Location	Temperature of flue gas (K)	Density (kg/m^3)	Viscosity (kg/ms)	Specific heat (J/kg-deg C)	Thermal Conductivity (W/m-K)
HP FSH	683.15	0.5150	3.2694E-05	1077.6823	0.0477
HP PSH	651.15	0.5403	3.1667E-05	1072.6582	0.0461
EVAP	562.15	0.6258	2.8778E-05	1049.2121	0.0417
LP SH	484.65	0.7259	2.6083E-05	1033.3022	0.0373
ECO	462.65	0.7604	2.5250E-05	1030.3715	0.0360
LP EVAP	428.65	0.8207	2.3861E-05	1025.7660	0.0339
CPH	389.65	0.9028	2.2278E-05	1021.1605	0.0315

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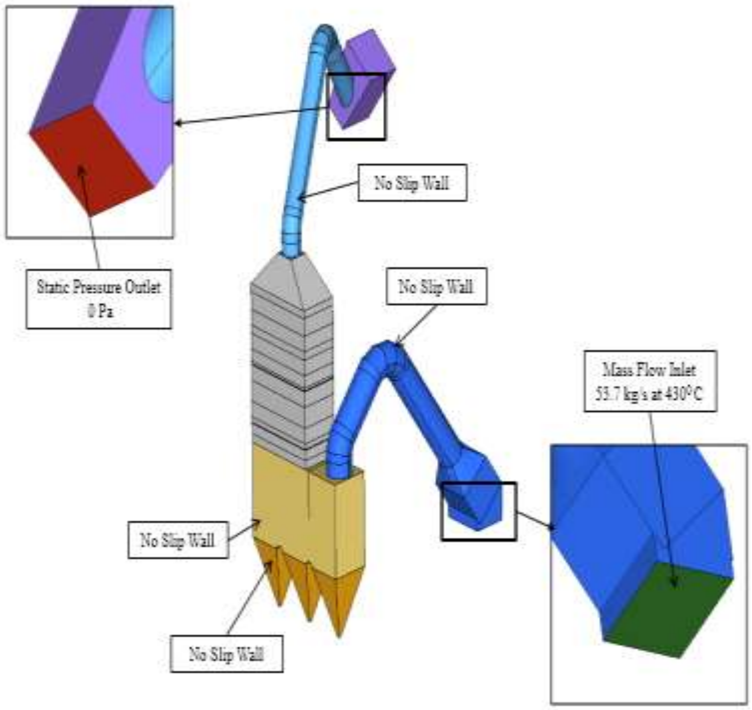

Case Description

After first iteration of analysis following observations were made.

- Flow recirculation has been observed at inlet of boiler after deduster,
- No flow region is observed in 2nd hopper of the boiler.
- Flow separation has been observed at inlet duct
- High velocities were observed on mid-plane of deduster
- High velocity patches were observed at outlet duct

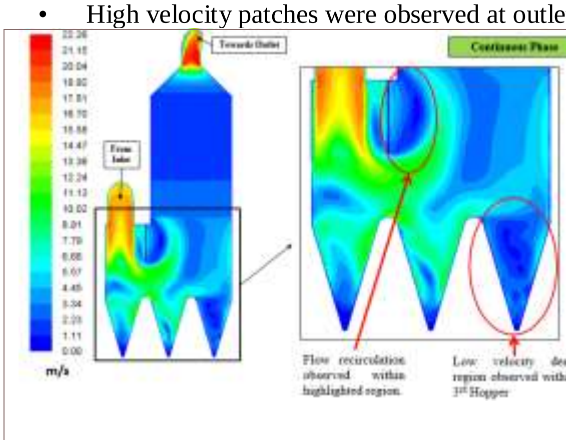

Fig.3.3 Contours Coloured by Velocity Magnitude, m/s on Y-Plane

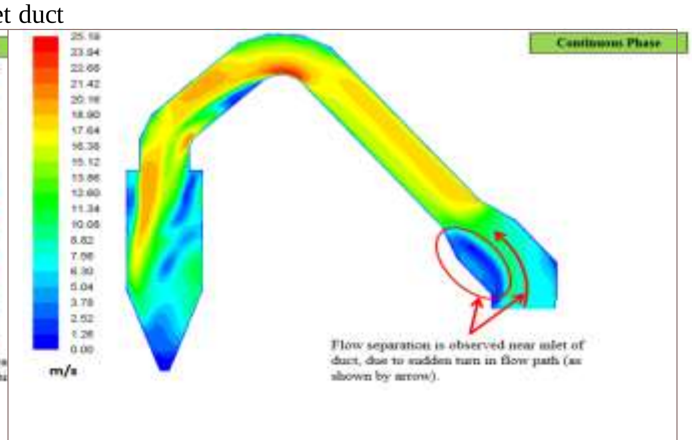

Fig.3.4 Contours Coloured by Velocity Magnitude, m/s on X-Plane

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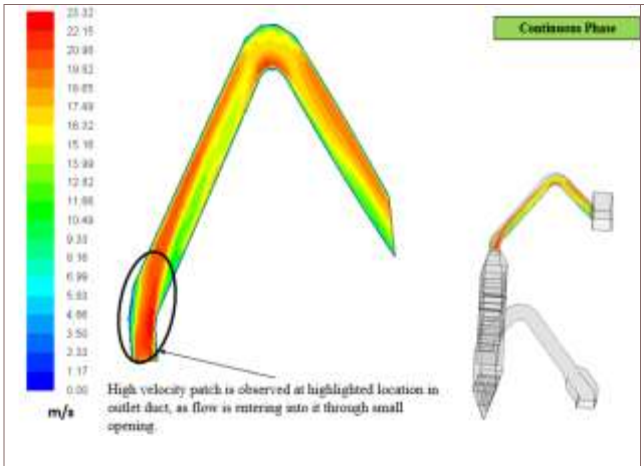


Fig.3.5 Contours Coloured by Velocity Magnitude, m/s on X-Plane Outlet Side

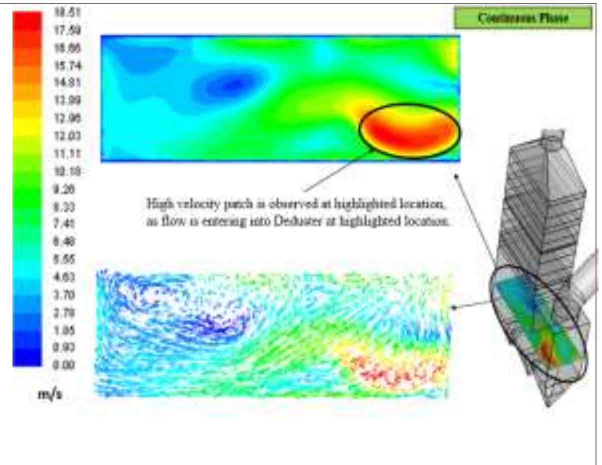
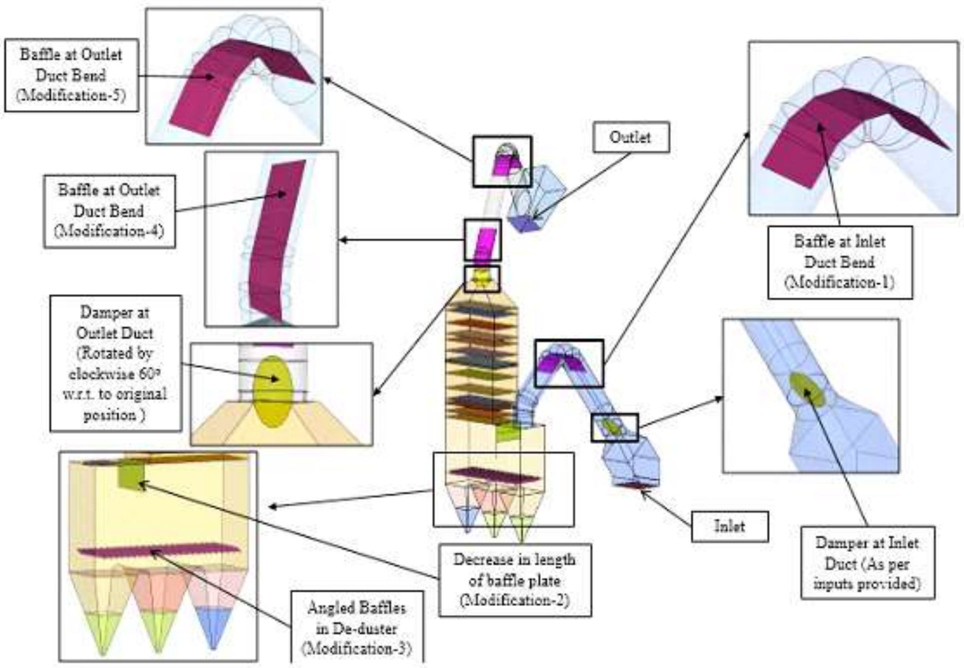


Fig.3.6 Contours & Vectors Coloured by Velocity magnitude, m/s on Deduster Mid Plane

Modified Case

To evade the snags that were perceived as categorised above, baffles were introduced in certain areas

- Baffle at Inlet duct bend (invert)
- Baffle plate separating desusting area & boiler
- Angled baffles above hoppers
- Rotation of outlet damper by 60 deg
- Baffle at outlet of duct
- Baffle at outlet duct bend (invert)



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III. RESULTS AND DISCUSSION:

Total Pressure Drop (mmWC) across Various Sections

Below table gives us insight of total pressure drop for both the base case and modified case (with baffles) acrocess various sections inlet ducting, boiler & outlet ducting.

Location	Total Pressure Drop (mmWC)	
	Base Case (Without Baffles)	Modified Case (With Baffles)
Inlet Duct (Inlet to Plane-1)	0.887	1.436
Plane-1 to Plane-2	37.660	38.333
Outlet Duct (Plane-2 to Outlet)	12.581	13.802

Table.5.2 Pressure drop across Various Sections

Velocity magnitude & contours across complete boiler

Velocity magnitude in contours & vectors across boilers were shown in below figures, from below figures it is evedent recirculation hapenning at inlet of boiler is eluded by decresing bafle length after deduster hopper and uniform velocity distribution is identified across the inlet, hopper and flow path. Also flow directed to one corner at outlet of boiler is avoided with bafle plate.

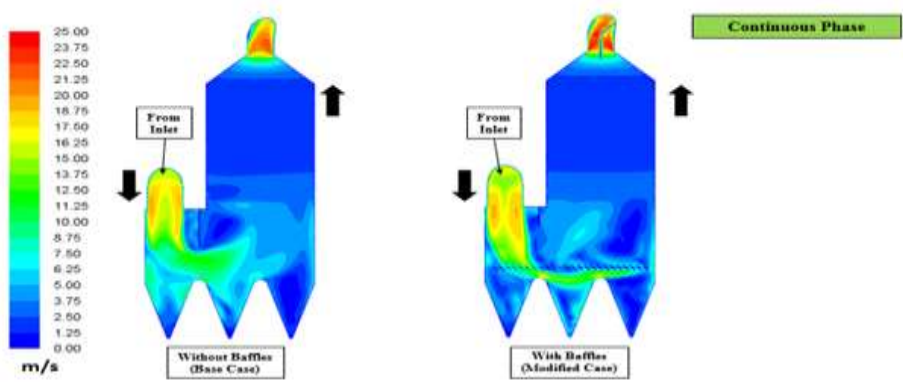

Fig5.2 Contours Coloured by Velocity Magnitude, m/s on Y-Plane

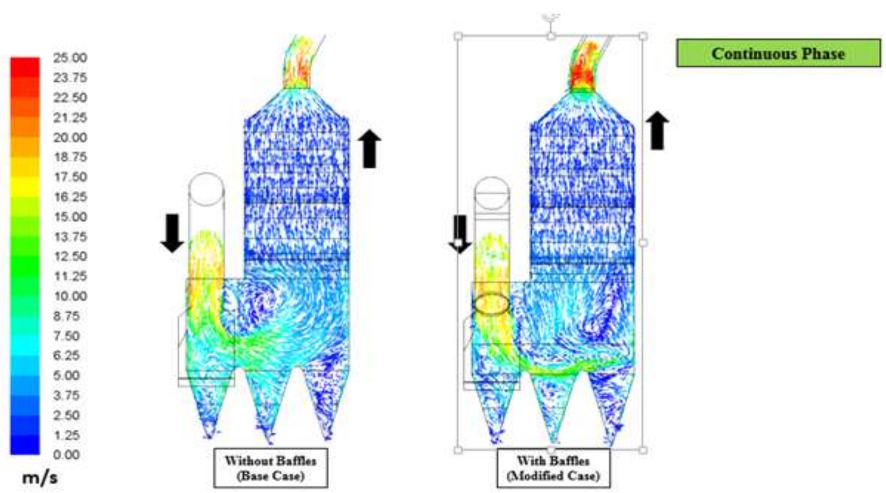

Fig5.3 Vectors Coloured by Velocity Magnitude, m/s on Y-Plane

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Velocity magnitude & contours across dedusting area

Below figures showing contours & vectors by velocity magnitude elaborote diferencess across dedusting area, from below figures it is evedent recirculation hapenning at inlet of boiler is eluded by decresing bafle length after deduster hopper.

Also uniform velocity distribution is identified across the inlet, hopper and flow path with indiduction of angular baffles above hoppers

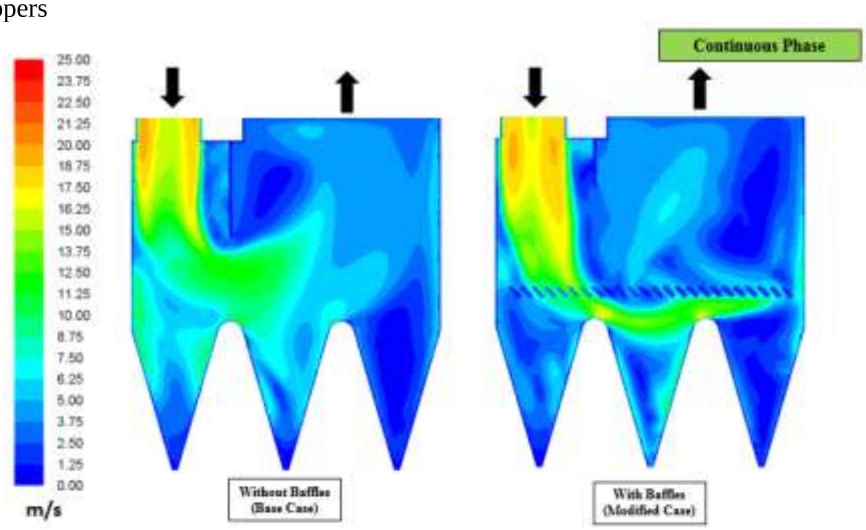

Fig 5.4 Contours Coloured by Velocity Magnitude, m/s on Y-Plane

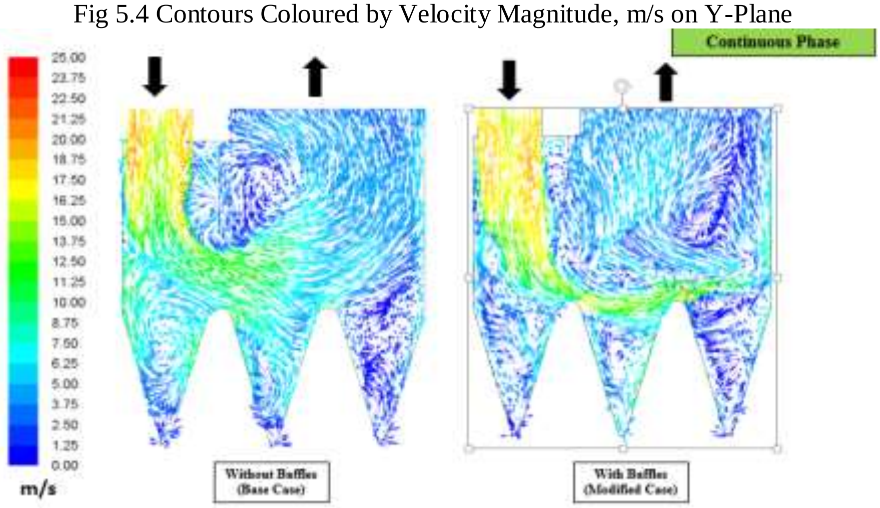

Fig 5.5 Vectors Coloured by Velocity Magnitude, m/s on Y-Plane

Velocity magnitude & contours across inlet & outlet

Contours & vectors by velocity magnitude across inlet & outlet ducting were plotted in below figures, where in we can observe concentration of higher velocities at invert portion of inlet ducting which could cause erossion in ducting is avoided with a baffle.

Similar is the case with outlet ducting we can spot concentration of higher velocities at invert portion as well as entry portion of which could cause erossion in ducting is eluded with a baffle. Uniform velocity distribution is also identified across the ducting with institution of baffles in the ducting

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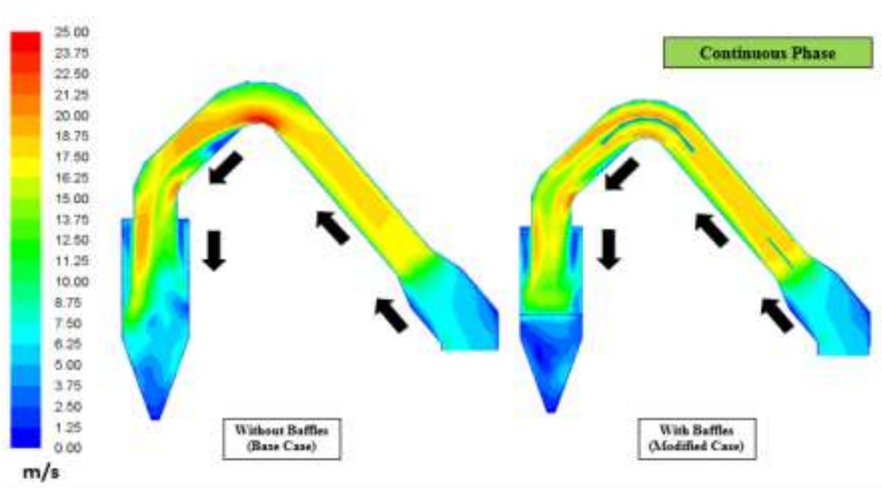

Fig Contours Coloured by Velocity Magnitude, m/s on X-Plane

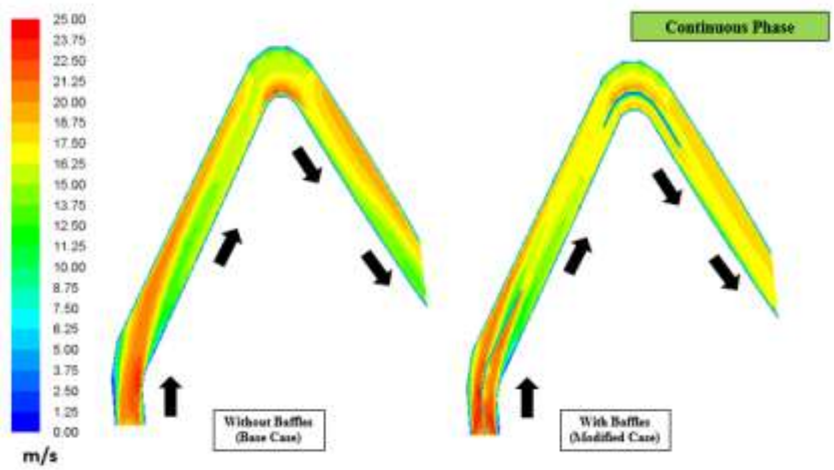

Fig Contours Coloured by Velocity Magnitude, m/s on X-Plane Outlet Side

Dust Particle Separation Efficiency

- Generally duct collection efficiency in deduster is found in between 35% to 40%. As the dust of cooler is abrasive in nature, the erosion on tube bundles & coils of HP Final super heater, HP primary super heater, HP evaporator, LP super heater, Economizer, LP evaporator and condensate pre-heater tube bundles can be redced and life of the same can be improved. Below tables exemplifies total particle separation efficiency is improved from **34.77%** in "Base Case (Without Baffles)", whereas in "Modified Case (With Baffles)" total particle separation efficiency of **57.38%** is observed for given particle loading and sizes.

Sr. No.	Particle Diameter (micron)	Distribution	Dust Mass Flow Rate (kg/s)	Dust Mass Flow Rate at Hopper Surfaces (kg/s)	Diameter wise Separation Efficiency (%)	Distribution wise Separation Efficiency (%)
1	100	0.8	1.667	0.53	31.58	25.26
2	200	0.2		0.79	47.55	9.51
					Final Total Separation Efficiency (%)	34.77

Table. Total particle separation efficiency in Base Case (Without Baffles)

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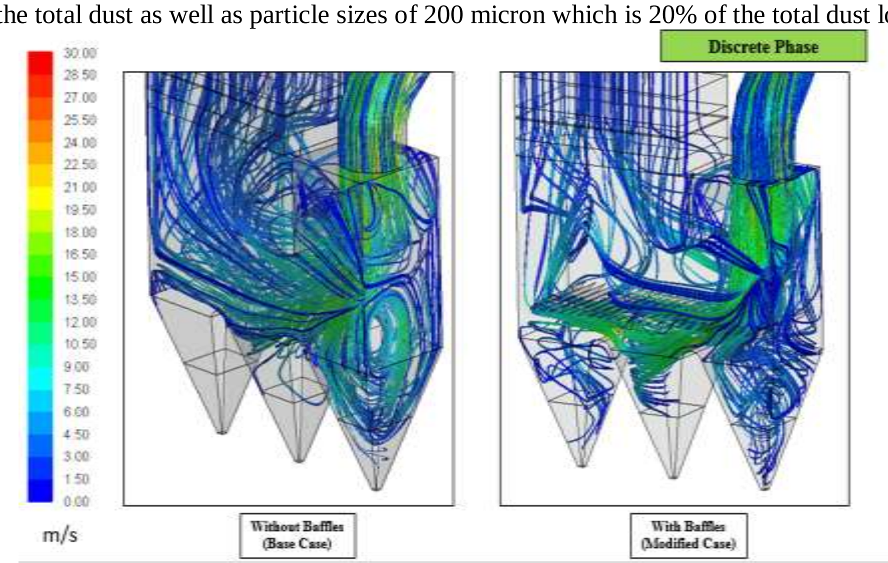
Sr. No.	Particle Diameter (micron)	Distribution	Dust Mass Flow Rate (kg/s)	Dust Mass Flow Rate at Hopper Surfaces (kg/s)	Diameter wise Separation Efficiency (%)	Distribution wise Separation Efficiency (%)
1	100	0.8	1.667	0.94	56.36	45.09
2	200	0.2		1.02	61.47	12.29
					Final Total Separation Efficiency (%)	57.38

Table. Total particle separation efficiency in Modified Case (With Baffles)

Below outlines represents particles track colored by Velocity magnitude for particle sizes of 100 micron which is 80% of the total dust as well as particle sizes of 200 micron which is 20% of the total dust loading.



IV. CONCLUSIONS

The particle flow pattern in solid-gas multiphase flows is so complicated and strongly depends on so many parameters, such as gas flow velocity, particle density, geometry of the duct and sizes, normal restitution coefficient and mass flow rate of the particle.The position of the inlet and outlets of the gas flow material plays a dominant role in the particle behavior and flow turbulence. From the CFD simulation it is observed that there are some recirculation patches after deduster hoppers and high velocity regions in ducting, deduster mid plane and invert portions of duct. Modifications were done based on simulation, for example reducing the high velocity regions by introducing baffles within duct for avoiding wear of duct wall due to particle hitting on wall, maintaining the pressure drop across AQC within permissible limit Choosing a right velocity for the industrial applications of multiphase flows, depends highly to the density of the particles and this factor plus the duct length determine the needed flow pattern and velocity to ensure the momentum required to convey the material. This helps in improving the flow uniformity at tube bundle inlets for effective working of heat exchanger bundle Present simulation involves two phases in a flow, which are gaseous phase (flue gas as a continuous phase) and solid phase (ash particles as a discrete phase). Hence flue gas ducting problem is solved using numerical calculations by Euler-Lagrange approach i.e. Discrete Phase Modelling (DPM) approach. In Lagrangian discrete phase model or DPM, fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field. The dispersed phase (ash particles) can exchange momentum, mass, and energy with the fluid phase (flue gas). This CFD simulation has given clear idea of dust circulation inside the hoppers and with introduction of angular baffles in mid plane the dust separation efficiency of de-duster is improved.

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