# Mathematical Modeling and Analysis of Plasma Combustion System with Various Operational Parameters and Mesh Refinement Using Fluent

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**ABSTRACT**

Plasma combustion holds promise to replace an old conventional ignition system in thermal power generation with a more efficient and environmentally friendly method. This investigation utilizes computational fluid dynamics (CFD) simulations in ANSYS Fluent to examine the effects of operational parameters on plasma combustion systems. The parameters considered include mass flow rate, wall temperature (thermal wall enhancement), and mesh refinement. Answering questions arise, the flow and reaction characteristics are simulated with the realizable k-epsilon turbulence model and P-1 radiation models by varying the above parameters for temperature, pressure, velocity fields, and emissions. The following findings were drawn: wall temperature is the most influencing parameter-one way being higher temperatures, leading to high combustion efficiency, pressure, and temperature while drastically reducing NOx emissions thanks to a more complete combustion process; increase in mass flow rate increases performance but with lower priority; mesh refinement from coarse to fine grids improves the resolution and accuracy only, while the overall trend of results remains almost the same, proving its usefulness in accurate numerical modelling. The two combustion cases suggest that plasma combustion has a better thermal performance and, therefore, significantly lower emissions of $CO_2$ and NOx. This carries an environmental and economic rationale since these plasma systems use electrically-induced plasma to ignite the flames or stabilize the flame without the need of a costly oil-based fuel. On the whole, the result stresses the promise of plasma combustion systems as a clean, efficient, and cost-effective way to carry out modern thermal power applications that satisfy energy sustainability goals and strict environmental standards.

***Key words**: Repowering, Thermal power plant, Energy, Plasma combustion Plasma CFD, Fluent etc.*

## 1. INTRODUCTION

Presence of gases produced by combustion in the flue gas stream requires dilution before undergoing analysis. The data obtained would be a true representation only after such a dilution procedure. Dilution of flue gases consists of mixing the gas with a clean, inert gas in a special probe and/or bag arrangement. A mixing and sampling probe is inserted in the chimney stack and is equipped with an interconnecting hose leading to a sampling bag. The volume of dilution-air added is substantially greater than the volume of flue gas collected; therefore, the diluted sample is substantially homogeneous. At very high sampling rates, the quality of the mixture in the probe and bag is affected by turbulence; as a consequence, samples do not conform to the EEC standards and their results are questionable. Other approval standards exist for dilution arrangement. However, these are rarely, if ever, used and reluctance exists to refer to these methods in a strict technical sense.

Thermo Chemical Plasma Preparation of Coals for Burning (TCPPCB) is one of the promising technologies. The aforementioned TPP issues are resolved by this technique. There are two primary steps in the TCPPCB technology's realization. Numerical simulations are used in the first, while full-scale tests of coal combustion with plasma assistance in a TPP boiler are used in the second. The 200 MW Gusinoozersk TPP (Russia) boiler was chosen for the full-scale trials as well as the numerical analysis. The architecture of the concept includes a PFS chamber where arc plasma activates a certain amount of pulverized solid fuel (pf) that is isolated from the primary pf flow (Fig.1). For heating fuel mixtures, eliminating volatile coal arc components, and partially gasifying carbon, the air plasma flame provides additional oxidation and heat in addition to a high-temperature, radical-rich environment. This actively blended fuel has the ability to ignite the furnace's primary PF flow. This technique allows for boiler start-up and flame stabilization without the need for additional highly reactive fuel.

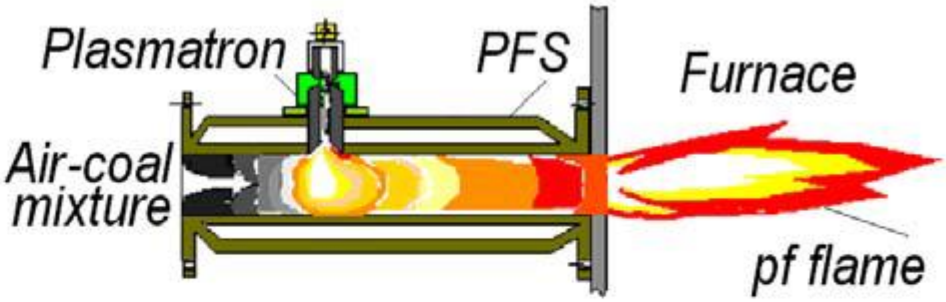


Figure 1 Arch plasma within a designated space

With steam generation capacities ranging from 75 to 670 TPH, plasma-fuel systems (PFS) have undergone extensive testing for their efficacy in boiler plasma start-up and flame stabilization across a variety of pulverized coal burners and 27 power boilers in multiple countries. A wide range of coal types, including bituminous, anthracite, brown coal, and different blends, were used in these experiments. The calorific values, ash content, and volatile matter content of the coals used in the tests varied significantly, ranging from 6700 to 25,100 kJ/kg, 15% to 48%, and 4% to 50%, respectively. The versatility and resilience of PFS technology in managing various coal qualities while preserving combustion stability and performance are highlighted by this wide range of fuel properties.

## 2. LITERATURE REVIEW

**Beyca n Ibrahimoglu, M. Zeki Yilmazoglu, Ahmet Cucen [1]** This study used computational modeling to assess the viability of repowering a thermal power plant boiler using plasma combustion systems. Plasma combustion systems installed directly on the boiler surfaces took the place of traditional fuel-oil burners in order to lower the plant's energy usage. Boundary conditions and design parameters were included in the thorough documentation of the integration process. Porous media models that represented the superheater and economizer tubes were used to analyze pressure losses across the system's components. Thermoflex software was used to accurately calculate the heat loads for each boiler segment by simulating the power plant in accordance with standard design protocols. Numerical simulations were then performed in ANSYS Fluent using these outputs to compare the furnace's temperature contours, velocity vectors, and isosurfaces. Incorporating the plasma system resulted in a slight decrease in input velocities across various domains. Interestingly, even in cases of overheating, convective surfaces were not adversely affected by the extra energy input from the plasma combustion system. Thermal power plants (TPPs) in Almaty, Shakhtinsk, and Ust-Kamenogorsk (TPP-2 and TPP-3) are investigating further advancements in plasma combustion technology. Direct-flow and vortex plasma-fuel systems (PFS) are being considered for use in coal-fired boilers. These plasma systems use coal directly, in contrast to traditional techniques that depend on fuel oil or natural gas for ignition and flame stability. A high-energy plasma torch gasifies the coal and partially oxidizes the char in the PFS, which receives a portion of the coal-air mixture. The majority of carbon is transformed into carbon monoxide due to a lack of oxygen, creating a highly reactive fuel (HRF) that is made up of partially oxidized char particles and flammable gases. When this HRF enters the main combustion chamber, it ignites quickly. Through simulations and practical testing, the application of PFS in current TPPs has been confirmed to be technically feasible, environmentally beneficial, and energy-efficient—all with out the need for auxiliary oil-based ignition systems.

## 3. OBJECTIVE OF THE STUDY:

In present study we will investigate the plasma combustion model with various operating parameters like mass flow rate, Turbulence intensity and wall enhancement for the better mixing and penetration of Air/Fuel mixture. In the second step we will also investigate the mesh refinement of the plasma combustion model for the better accuracy of the simulation results.

## 4. METHODOLOGY

### 4.1 CFD METHOD APPLIED

ANSYS 14.5 was used to simulate the model and pre-process the necessary geometry configurations. The methodology employed in the CFD simulations for this specific investigation is demonstrated in the section that follows.

GEOMETRY OR MODEL FORMATION IN STEP I

In order to save computational time, the geometry used for the simulation is only a subset of the entire exhaust gas system because the main goal of the study is to determine the NOx percentage. The ANSYS-created model is displayed below: -

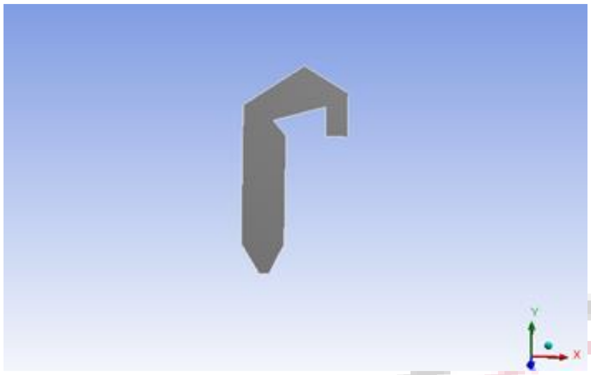

Figure 4.1 CAD Model

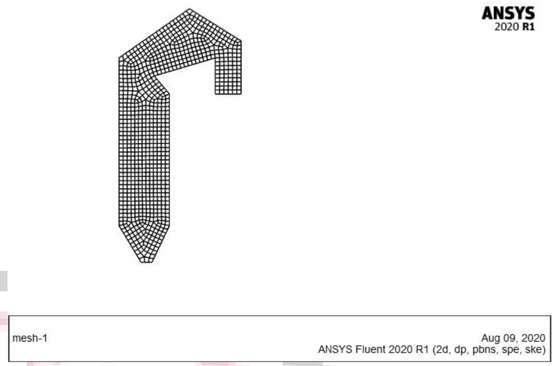


Figure 4.2 Model of Mesh

STEP 2

MESH FILE – To be Meshed

STEP 3 CHECKS THE MESH: -

The console shows the outcomes of several mesh quality checks. To ensure mesh integrity, it is crucial to confirm that the stated minimum cell volume is a positive value. Additionally, to ensure consistency with the geometry of the model and simulation parameters, set the mesh unit to millimeters (mm).

METHODS

1. In response to pressure
2. 3D models are used.
3. Gravity enables

MODEL

1. The equation for energy is functional.
2. The K-Epsilon turbulence model was used.
3. P-1 is utilized since the radiation model operates more quickly. However, more precise outcomes in common models can be obtained by using the DO radiation model.
4. Eddy dissipation and finite rate in turbulence chemistry. The species model makes use of interactions.

STEP 4 SETUP FOR SIMULATION

4.2 Boundary conditions

[1] INLET– 1. Fuel Inlet- Mass flow rate -0.5, 1.0 and 1.5 Kg/s

2. Air Inlet – Stoichometric Ratio calculated by CFD

[2] Wall Enhancement – Wall Temperature – 500, 1000 and 1500 k

[3] Mesh Refinement – 1. Coarse – Element size – 3.21e-03

2. Fine Mesh - Element size – 2.03e-04

4.3 MATERIAL

Properties of SOMA/EYNES coal.

| | |
|---|---|
| **Proximate analysis (as received) [wt.%]** | |
| Moisture | 25.22 |
| Volatile matter | 32.83 |
| Fixed carbon | 23.55 |
| Ash | 18.4 |
| **Ultimate analysis (dry basis) [wt.%]** | |
| C | 39.48 |
| H | 2.95 |
| N | 0.59 |
| O | 12.83 |
| S | 0.53 |
| Lower heating value [kJ/kg] | 14,248 |

1. Mixing law is used and chemical kinetic mechanism is used for NOx evaluation.
2. Two polynomial coefficients for thermal conductivity should be defined.
 (a) 0.0057894  (b) $5.1247*10^{-6}$
3. Viscosity polynomial coefficient
 (a) 8.945e-07  (b) 3.2145e-9
4. Determine the stable domain for the absorption coefficient.
5. 1.5e-9 is the scattering coefficient.

STEP 5 SOLUTIONS

Method

1. Coupled
2. Presto model is used: -

Presto is best suited for simulations of buoyant flow, where the velocity vector close to the walls may not match the wall surface precisely because the boundary layer is assumed to have uniform pressure. Only hexahedral or quadrilateral mesh elements can use this scheme because it can precisely capture pressure variations in these flow conditions: -

Pseudo transient is enabled

1. 0.1 The time scale factor for turbulent dissipation rate and turbulent kinetic energy
2. The time scale factor for species and energy is 10.

NOTE: - To converge the solution in fewer iterations, the energy and species equation uses a larger time scale size.

SETTING UP THE SOLUTION: - The solution is set up.

RUN CALCULATION: - Start the calculation for 1500 iterations.

## *5.* Results & Discussion

**CHAPTER 5**

**RESULTS**

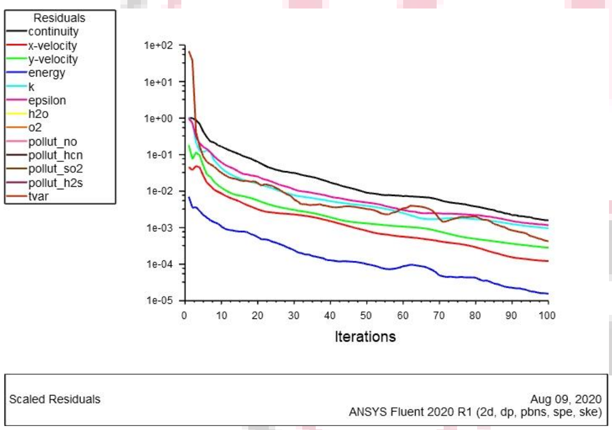


Fig. 1 Progress of Analysis Scales Residuals

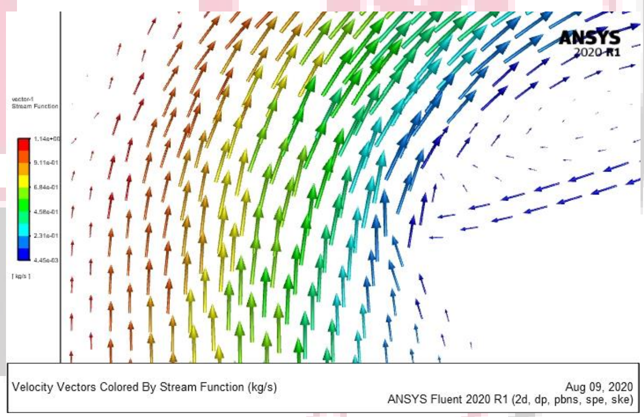


Fig. 2 Velocity Stream line Function

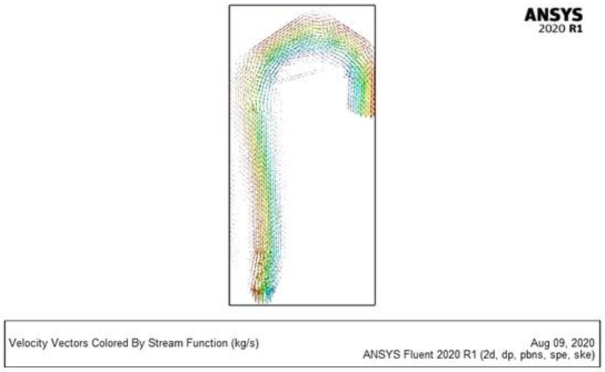


Fig. 3 Velocity Vector contour by Stream Function

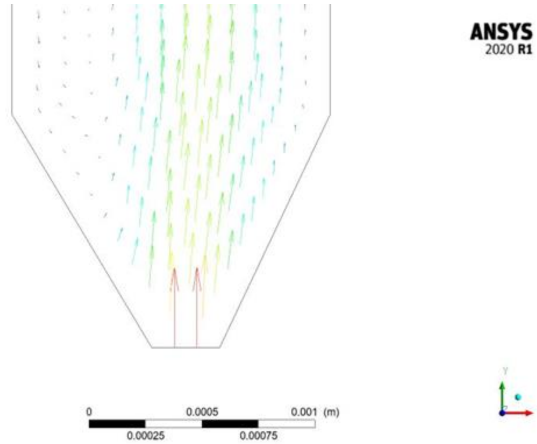


Fig. 4 Velocity Vector contour (close up) by Stream Function

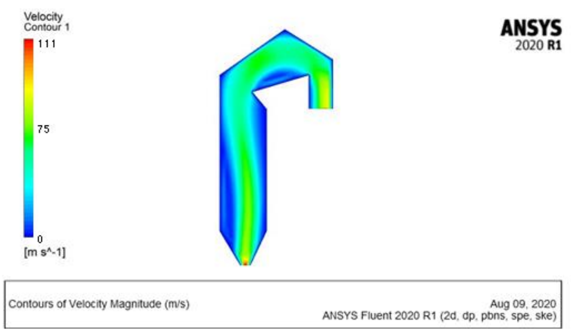


Fig. 5 Velocity Magnitude (m/s) of Case 1

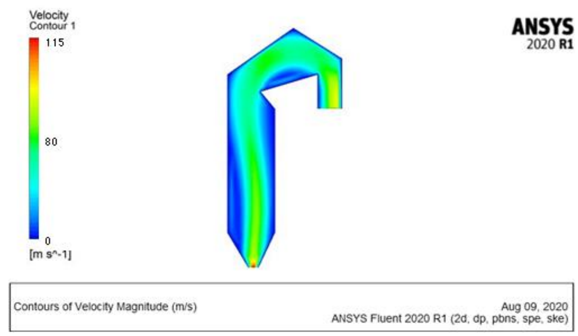


Fig. 6 Velocity Magnitude (m/s) of Case 2

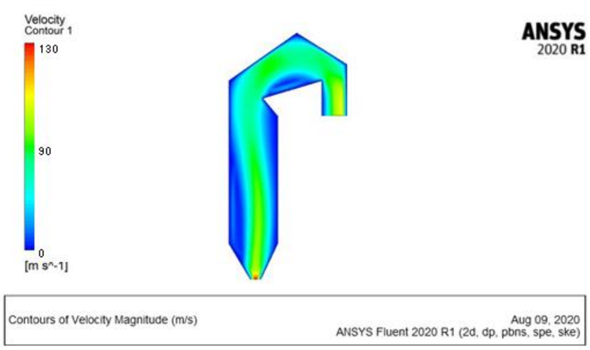


Fig. 7 Velocity Magnitude (m/s) of Case 3

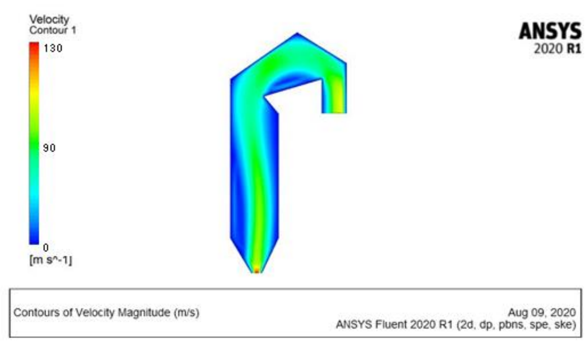


Fig. 8 Velocity Magnitude (m/s) of Case 4

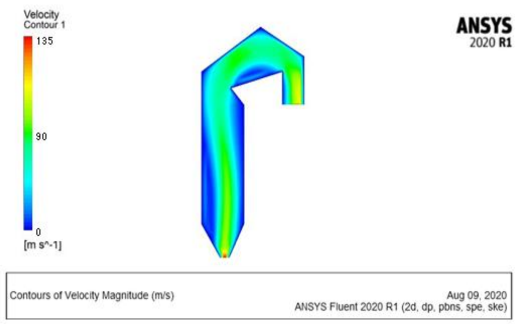


Fig. 9 Velocity Magnitude (m/s) of Case 5


Fig. 10 Velocity Magnitude (m/s) of Case 6

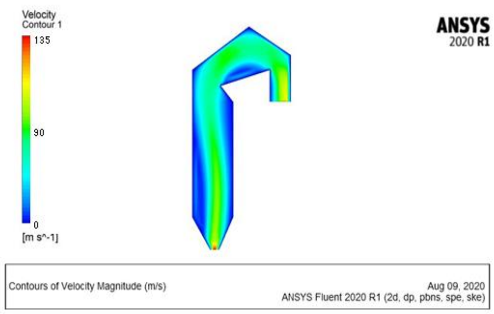


Fig. 11 Velocity Magnitude (m/s) of Case 7

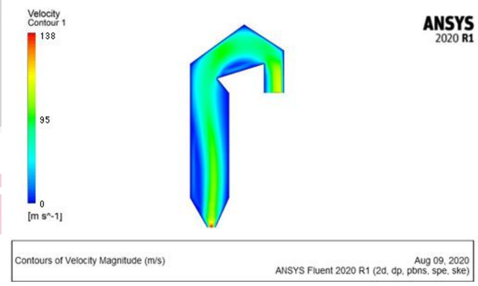


Fig. 12Velocity Magnitude (m/s) of Case 8

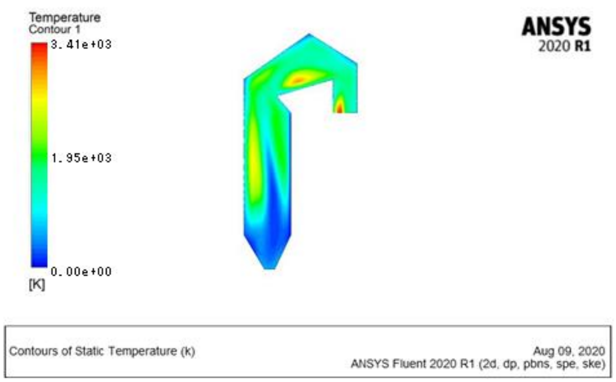


Fig. 13 Temperature (K) of Case 1

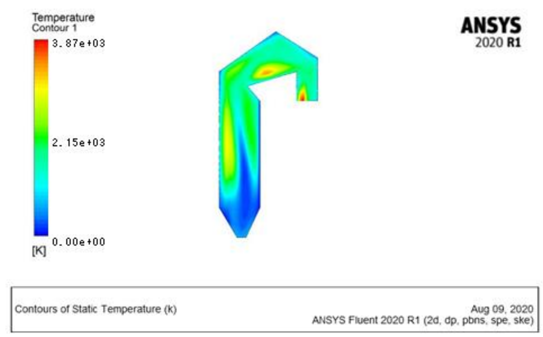


Fig. 14 Temperature (K) of Case 2

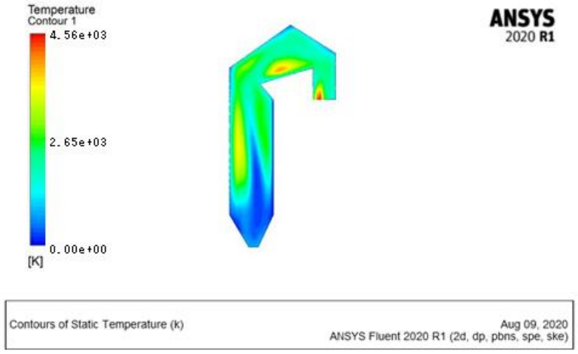


Fig. 15 Temperature (K) of Case 3

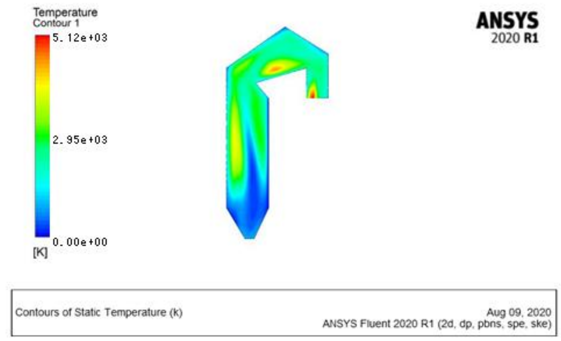


Fig. 16 Temperature (K) of Case 4

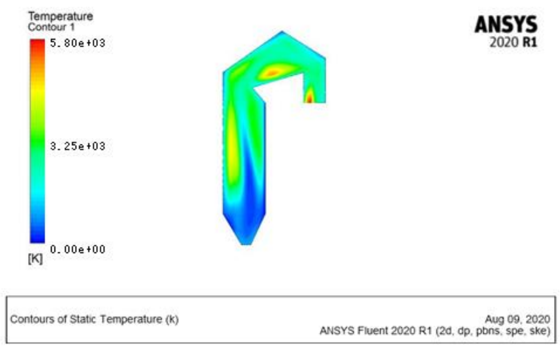


Fig. 17 Temperature (K) of Case 5

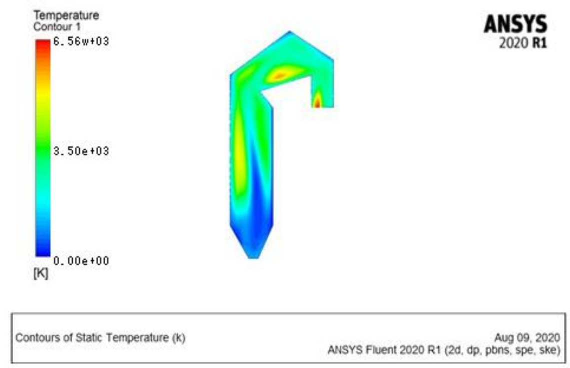


Fig. 18 Temperature (K) of Case 6

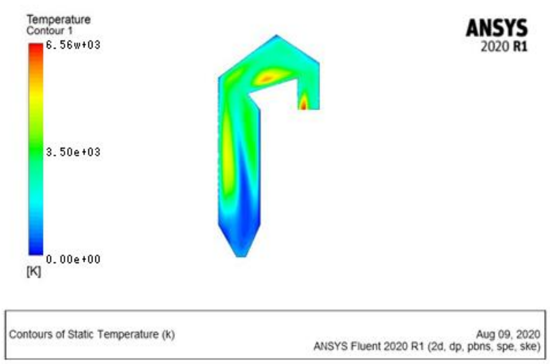


Fig. 19 Temperature (K) of Case 7

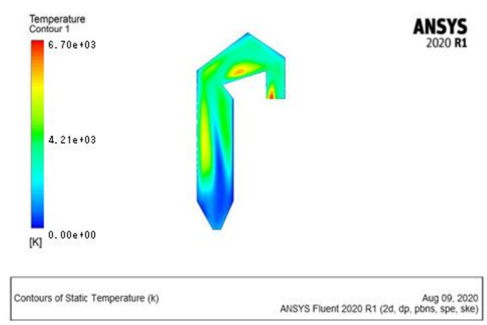


Fig. 20 Temperature (K) of Case 8

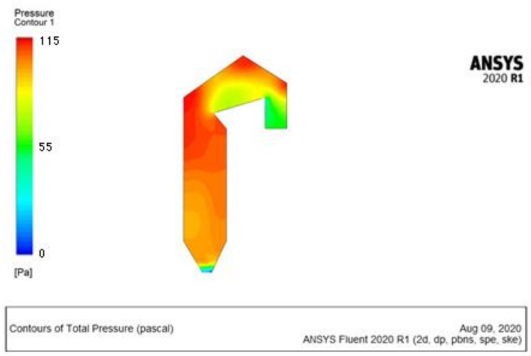


Fig. 21 Total Pressure (Pa) of Case 1


Fig. 22 Total Pressure (Pa) of Case 2

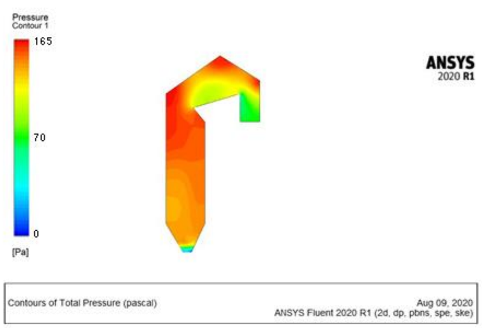


Fig. 23 Total Pressure (Pa) of Case 3

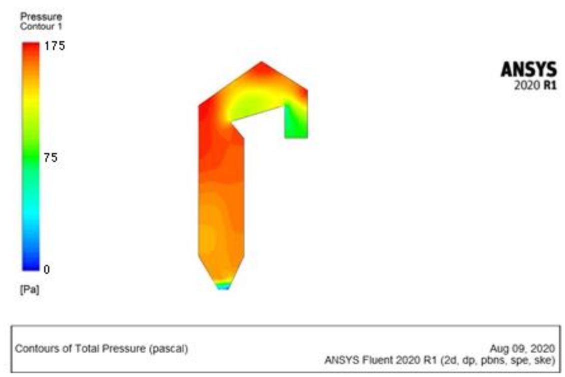


Fig. 24 Total Pressure (Pa) of Case 4

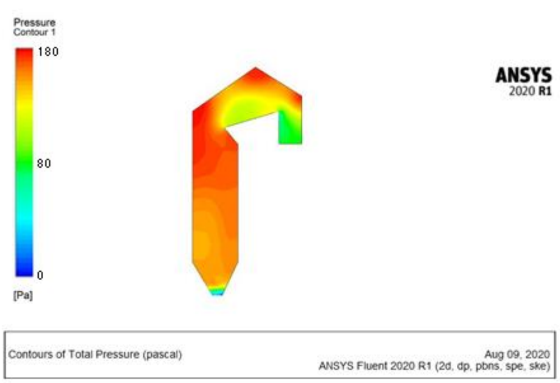


Fig. 25 Total Pressure (Pa) of Case 5

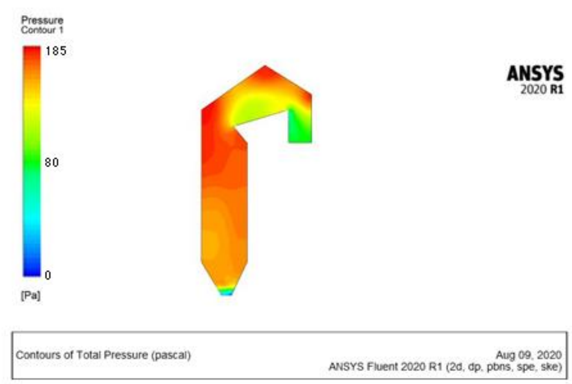


Fig. 26 Total Pressure (Pa) of Case 6

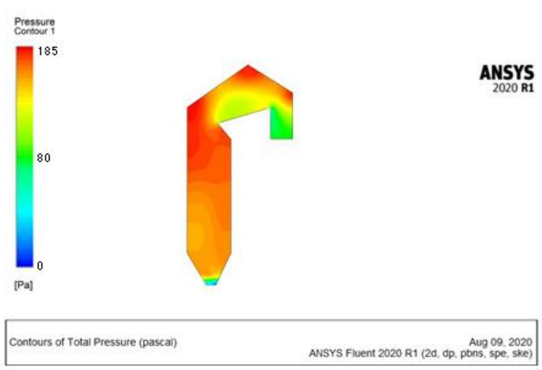


Fig. 27 Total Pressure (Pa) of Case 7

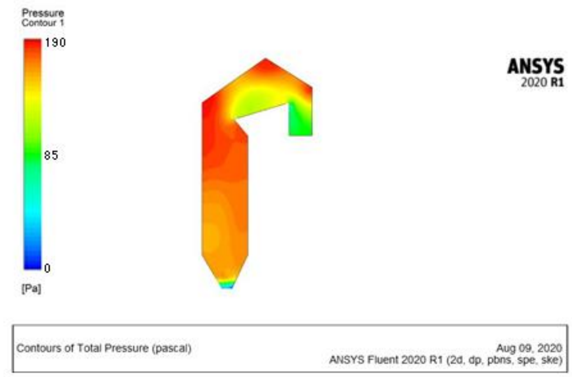


Fig. 28 Total Pressure (Pa) of Case 8

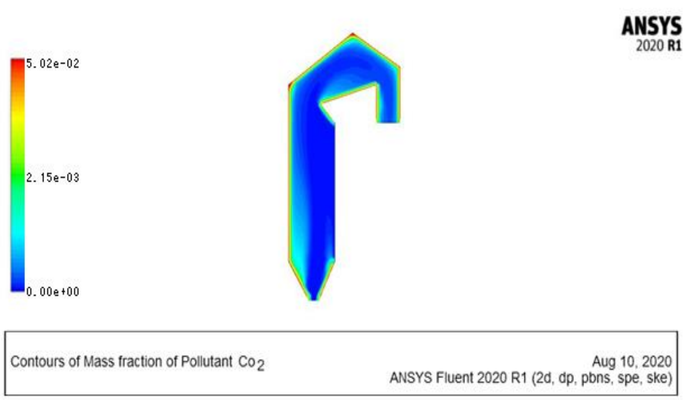


Fig. 29 CO2 mass fraction in Case 1

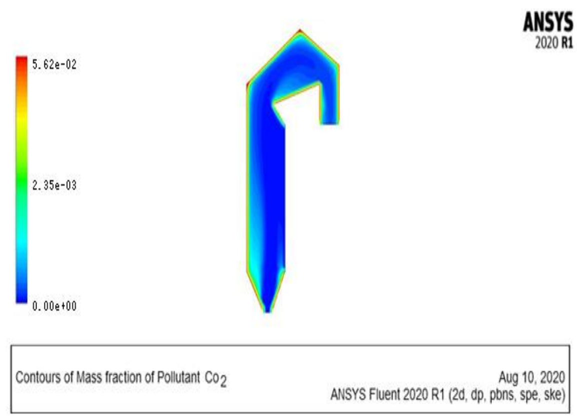


Fig. 30 CO2 mass fraction in Case 2

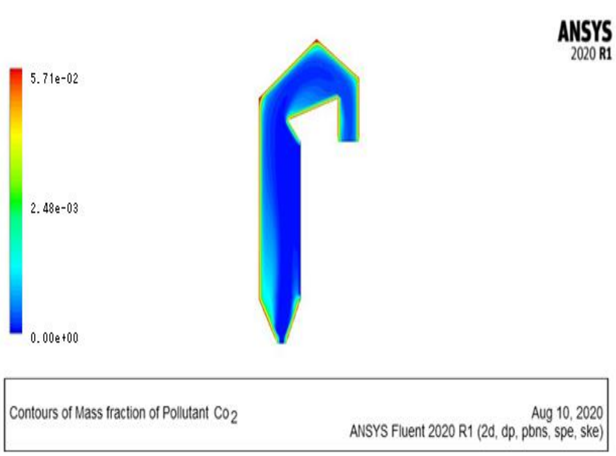


Fig. 31 CO2 mass fraction in Case 3

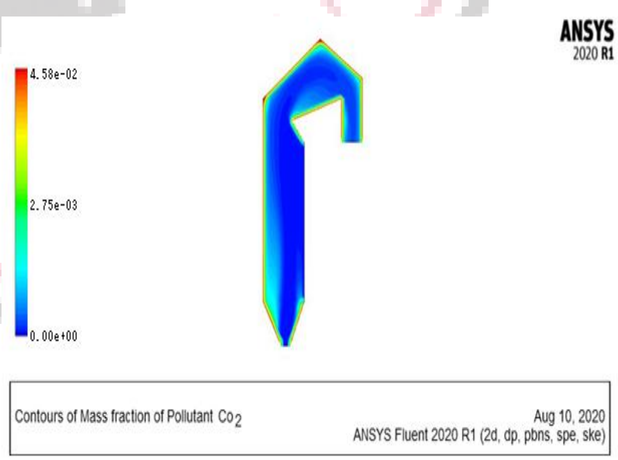


Fig. 32 CO2 mass fraction in Case 4

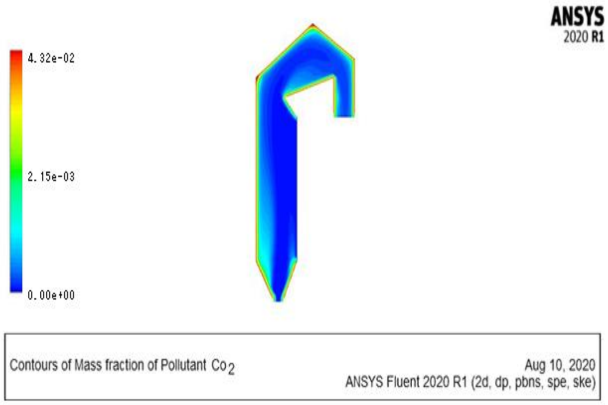


Fig. 33 CO2 mass fraction in Case 5

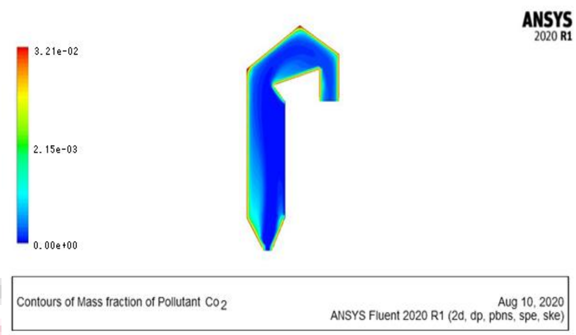


Fig. 34 CO2 mass fraction in Case 6

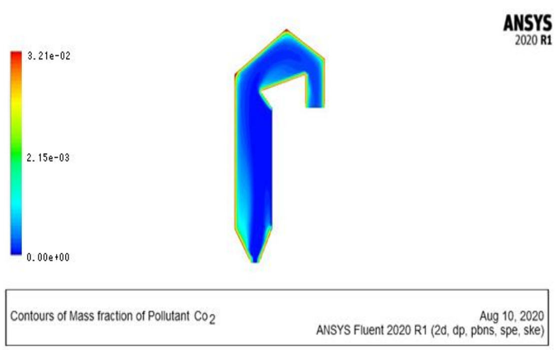


Fig. 35 CO2 mass fraction in Case 7

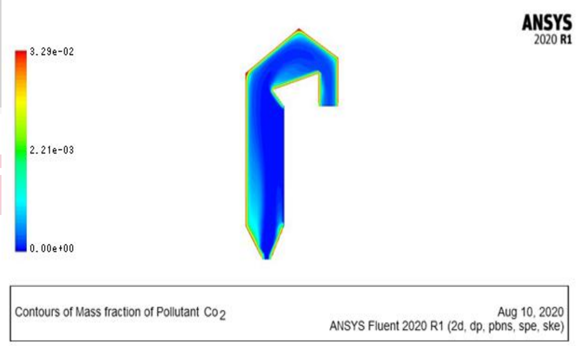


Fig. 36 CO2 mass fraction in Case 8

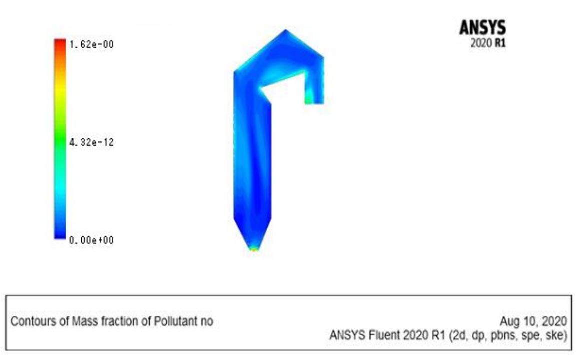


Fig. 37 Mass fraction of NO in Case 1

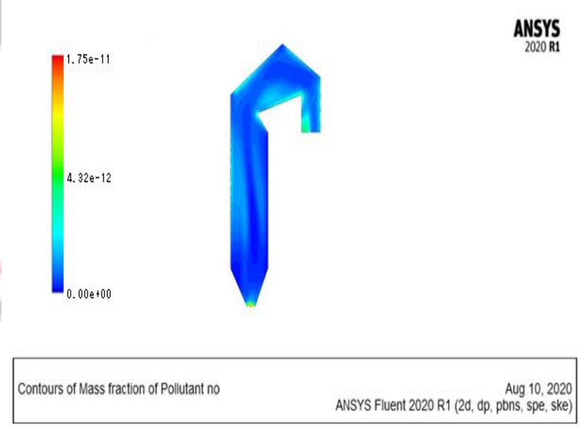


Fig. 38 Mass fraction of NO in Case2

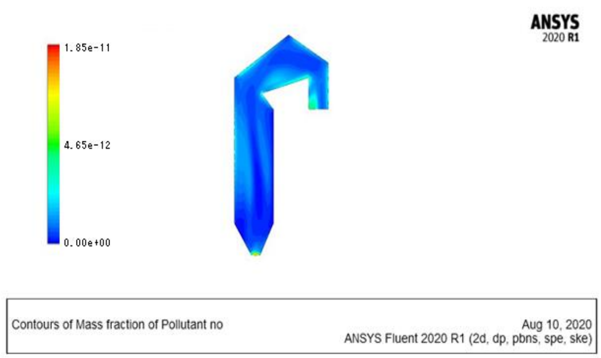


Fig. 39 Mass fraction of NO in Case 3

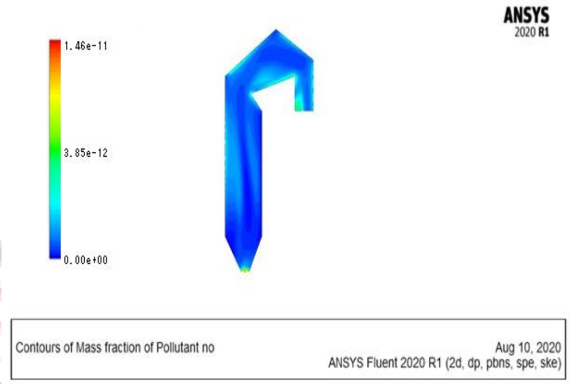


Fig. 40 Mass fraction of NO in Case 4

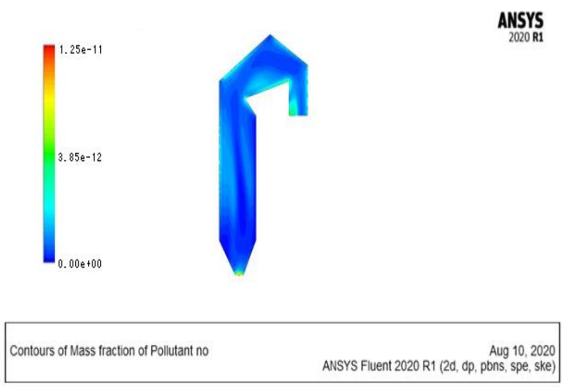


Fig. 41 Mass fraction of NO in Case 5

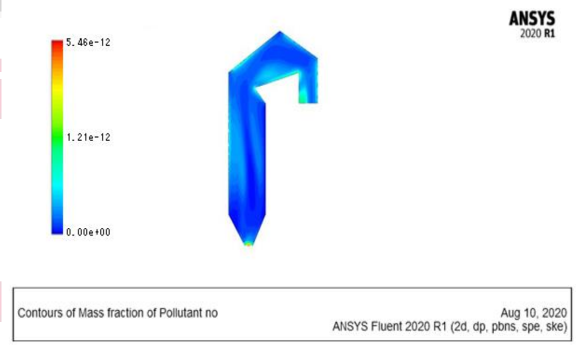


Fig. 42 Mass fraction of NO in Case 6

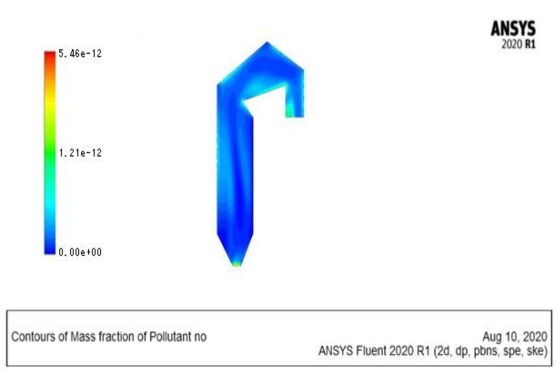


Fig. 43 Mass fraction of NO in Case 7

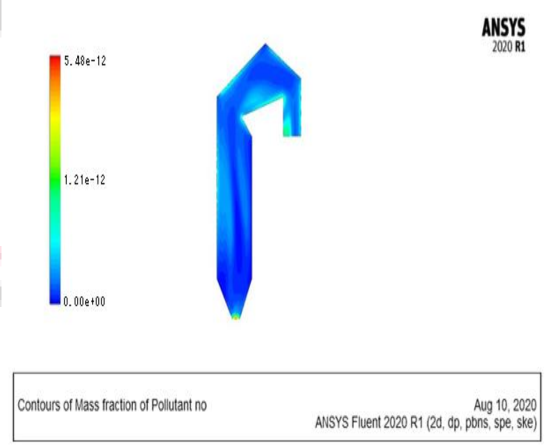


Fig. 44 Mass fraction of NO in Case 8

**Result Table**

| **Plasma Combustion Operational Parameters** | **Mass flow rate (Kg/s) Study No. 1** | | | **Wall Enhancement (K) Study No. 2** | | | **Mesh Refinement Study No. 3** | |
|---|---|---|---|---|---|---|---|---|
| | **Case1** | **Case2** | **Case3** | **Case4** | **Case5** | **Case6** | **Case7** | **Case8** |
| **Final Outcomes** | **0.5** | **1** | **1.5** | **500** | **1000** | **1500** | **Coarse** | **Fine** |
| **Temperature (K)** | **3410** | **3870** | **4560** | **5120** | **5800** | **6560** | **6560** | **6700** |
| **Total Pressure (Pa)** | **115** | **135** | **165** | **175** | **180** | **185** | **185** | **190** |
| **Velocity (m/s)** | **111** | **115** | **130** | **130** | **135** | **135** | **135** | **138** |
| **Mass Fraction of C02** | **5.02e-02** | **5.62e-02** | **5.71e-02** | **4.58e-02** | **4.32e-02** | **3.21e-02** | **3.21e-02** | **3.29e-02** |
| **Mass Fraction of N02** | **1.62e-11** | **1.75e-11** | **1.85e-11** | **1.46e-11** | **1.25e-11** | **5.46e-12** | **5.46e-12** | **5.48e-11** |

**CONCUSION**

The results table displays a comparison of the plasma combustion system's mesh refinement, wall enhancement, and different mass floe rates. Because the profile's combustion velocity slows down in plasma, the residence time of combustion increases, which helps reduce emissions because it allows for complete combustion and lowers the pressure drop in a stable system. Before and during the plasma combustion systems' integration, each burner stage's velocity profile was investigated. To guarantee mixing and turbulence, the flame must have a rotating property. Full combustion can be accomplished through turbulence and mixing. Lastly, we use chemical kinetics to evaluate NOx emissions and compute COx and NOx emissions from CFD simulation. The results table clearly illustrates the differences between conventional and plasma combustion, showing that the former reduces all emissions (COx & NOx). This is because the combustion is more thorough than it would be with conventional oil fuel. Plasma combustion is also a cost-effective method because it doesn't require oil for flame stability or startup. Plasma activation of coal particles enables more effective and ecologically friendly burning without the use of fuel-oil burners.

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