MILD combustion of oxygen fuel burner using impinging jet method

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Abstract
The possibility of oxygen-MILD combustion without preheating of oxidants is assessed numerically and experimentally in this paper. For the formation of oxygen-MILD combustion, jet impingement method was employed to enhance the internal recirculation flow effectively and also compensate the drawback which the momentum of oxygen becomes smaller than that of air combustion. And effects of impingement and reactant jet velocity were analyzed to investigate the extent of internal recirculation necessary for formation of oxygen-MILD combustion. Results show that as the velocity of oxygen increases, the stronger internal recirculation ratio \( K_V \) makes the oxygen jet more diluted leading to reduce the maximum temperature and high-temperature zone inside the combustion field. It is found that MILD combustion having a uniform temperature distribution can be formed at low oxygen velocity with increasing impingement angle. The Damköhler number at the oxygen velocity of 120 m/s approaches to 1 as the impingement angle increases and MILD condition of \( D_a < 1 \) and \( Re_t < 10,000 \) was satisfied at the oxygen velocity of 220 m/s. Diffusion jet flame to MILD combustion flame was observed experimentally as the impingement angle increases at the oxygen flow velocity of 120 m/s. But at higher \( V_{oxy} = 220 \) m/s, the effect of impingement angle is not critical, unlike \( V_{oxy} = 120 \) m/s. The experimental results clearly support various numerical results which can provide valuable data for designing the oxygen MILD based the furnace.

Keywords: MILD (Moderate or Intense Low oxygen Dilution) combustion, Oxygen flame, Jet impingement, Recirculation ratio \( (K_V) \), Pilot scale furnace, NO\(_X\) reducing technique

Nomenclature

| Symbol | Definition | Symbol | Definition |
|--------|------------|--------|------------|
| \( K_V \) | recirculation ratio | \( \psi \) | Oxygen jet analysis line |
| \( M_e(z) \) | mass flow rate of recirculated exhaust gas (Kg/s) | \( \varepsilon \) | Eddy dissipation rate (m\(^2\)/s\(^3\)) |
| \( M_F \) | mass flow rate of fuel (Kg/s) | \( \rho \) | Density (Kg/m\(^3\)) |
| \( M_O \) | mass flow rate of oxygen (Kg/s) | \( C_\mu \) | Constant of turbulent viscosity |
| \( D_a \) | Damköhler number | \( C_r \) | Chemical-reaction rate constant |
| \( Re_t \) | Turbulent Reynolds number | \( \kappa \) | Turbulent kinetic energy (m\(^2\)/s\(^2\)) |
| \( T_{si} \) | Self-ignition temperature (K) | \( \nu_t \) | Turbulent kinematic viscosity (m\(^2\)/s) |
| \( \Phi \) | Equivalence ratio | \( \mu_t \) | Turbulent viscosity (Kg/m·s) |
1. Introduction

Recently, the global warming has become a critical concern worldwide. In order to solve this problem, strict regulations have been proposed to reduce emissions of carbon dioxide (CO$_2$), such as a representative greenhouse gas (IPCC, 2014; UNFCCC, 2015). In spite of the development of renewable and environment-friendly energy technologies, the amount of using fossil fuels are still high occupying about 80% of global total energy consumption (IEA, 2017). In the combustion process of obtaining energy using fossil fuels, CO$_2$ emissions are an inevitable problem. Particularly CO$_2$ reduction in steel and iron industries which constitute a considerable part of the overall energy consumption throughout the process of heating or producing the steel has been considered as a very critical issue (Kundak et al., 2009; EPA, 2012). One of the possible ways which reduce the amount of CO$_2$ using fossil fuels is to use natural gas with low carbon content. According to the recent report from the IEA, the amount of consumption of natural gas tends to increase continuously in recent years and is expected to account for 40% of world energy consumption by 2040. Another way to reduce CO$_2$ emission can be thought to increase the thermal efficiency in energy-intensive industry like steel making process. As a method of increasing the thermal efficiency in these iron and steelmaking processes, the regenerative burner proposed by researchers (Katsuaki and Hasegawa, 1998; Webber et al., 1999) has been widely used to a heating furnace in steel industries. These regenerative burners have a repetitive process of preheating and diluting the supplied reactants by forced recirculation of the exhaust gas. This regenerative furnace system shows very energy efficient characteristics but it occupies a lot of space because of the complicated fuel and dilution gas supply system and also needs frequent overhauls. Recently, oxy-fuel combustion technology has been studied, which compensates the disadvantages of these regenerative burners and improves combustion thermal efficiency (Kiriishi et al., 2009; Villermaux et al., 2009). Oxy-fuel combustion absent of N$_2$ in the oxidant can reduce the heat loss to N$_2$ in air-fuel combustion and its radiation heat transfer is enhanced because of high concentrations of the CO$_2$, H$_2$O with higher radiation emissivity than N$_2$ in air combustion (Baukal, 2013). Because of these advantages of the oxy-fuel combustion, many researches have been carried out in order to apply oxy-fuel combustion technology to the steel making process (Schéele, 2010). Although the oxy-fuel combustion has many advantages, its adiabatic flame temperature is about 800K higher than the air combustion so that local high-temperature region sometimes deteriorates the quality of the products and damages the furnace wall. Oxy-fuel combustion theoretically doesn’t have any emission of NOX but there is a possibility of thermal NOX due to air leak during the heating process (Schéele, 2013). In order to solve above hot spot and thermal NOX emission problems in pure oxygen combustion, application of MILD (Moderate or Intense Low oxygen Dilution) combustion was considered for the low pollutant emission and high thermal efficiency (Cavaliere and Joannon, 2004). Formation of MILD combustion has normally characterized by conditions of a temperature of reactants above T$_a$ (self-ignition temperature) and an elevated reactant temperature under T$_a$ in the combustion process (Oberlack et al., 2007). These characteristics lower the gas temperature at hot zone like flame front resulting to reduce temperature sensitive NOX (Plessing et al., 1998). It is very important for MILD combustion formation to maintain the mass fraction of oxygen in the reaction zone low by a large amount of the exhaust gas recirculation (Tsuji et al., 2002). In this combustion regime, the stoichiometric flame temperature is lower and temperature fluctuations are small, and there is no luminosity or sound emission from the flame (Wünning and Wünning, 1997). MILD combustion called as HiTAC, FLOX, CDC has been studied by the various research group. Wünning investigated the formation of FLOX (Flameless Oxidation) defined by the preheating temperature of reactants and internal recirculation ratio (K$_r$). Also, Arghode and Gupta analyzed the effect of various furnace shapes and fuel/air flow rate and injection position on the formation of Colorless Distributed Combustion (Arghode and Gupta, 2010). And Dally et al. had conducted research on MILD combustion characteristics according to the dilution rate of supplied air and fuel (Dally et al., 2013). Many numerical simulations for defining the MILD combustion region were also conducted. Parente et al. had analyzed MILD combustion region through the Damköhler number (D$_a$), the ratio of a flow time scale to a reaction time scale, and showed MILD combustion can be formed in the region of D$_a$ ≤ 1 (Parente et al., 2008). Williams et al. defined MILD combustion as the distributed reaction region by the D$_a$ and Re$_f$ value based on the Kolmogorov scale (Turns, 2012). Most of MILD combustion studies carried out by using RANS (Reynolds Averaged Navier-Stokes) or LES (Large Eddy Simulation) (Parente et al., 2011; Parente et al., 2012; Christo and Dally, 2005) revealed the effects of dilution of oxidant by high-speed flow momentum and preheating temperature. Previous researches had usually focused on the formation of air-fuel MILD combustion by enhancing internal circulation flow and preheating the oxidizer at various combustion systems. However, the researches about the formation of MILD.
combustion using oxy-fuel combustion method are very scarce. And some researches for oxy-fuel MILD have been solely focused on laboratory scale burner system. In addition, the latest studies on oxy-fuel MILD combustion on a pilot scale have shown a trend to use coal rather than gaseous fuels, and high-speed jet and preheated oxidizer were used as a method for forming the MILD combustion (Feifei et al., 2018; Zhihui et al., 2017). In the present study, a possibility of MILD combustion on pilot scale furnace system is assessed without preheating of oxidants numerically and experimentally. Especially effects of impingement and velocity of oxygen and fuel jet were analyzed to investigate the extent of internal recirculation necessary for the formation of oxygen MILD combustion.

2. Experimental method and Numerical analysis

The most important factor for the formation of MILD combustion is the dilution of the oxidant. This kind of dilution can be achieved by higher flue gas recirculation compared to conventional air-fuel combustion. However, the oxygen flow rate for complete combustion is very lower than the air flow rate for air-fuel combustion. So we try to increase the flow velocity of oxygen and entrain the flue gas much more. And impingement configuration is used to increase the mixing effect by the jet collision of oxygen and fuel, which helps for higher momentum exchange between oxygen and fuel. In the Previous studies, for the formation of the mild combustion applied the either forcibly reducing the oxygen concentration (hot-coflow, FGR) or using the special type of furnace. The impinging method used in this study is an advantage in that the form of internal recirculation can be performed without the effect of the furnace shape. In the case of a parallel jet, the internal recirculation flow can vary depending on the location of the outlet. Also, in order to form the MILD combustion, the flow time scale should be reduced. When using the impinging method, the flow time scale can be reduced due to the forced mixing of fuel and oxidizer. The forced mixing causes the decrease of the eddy dissipation rate in reaction region. This impinging jet has already been applied to rocket engines and is known to have very good mixing effects (Sutton et al., 2011). In the case of an oxidizer as pure oxygen, which is not an air oxidizer, we have been applied impinging method, since diluting the oxygen concentration by internal recirculation is more difficult for forming the MILD combustion.

2.1 Experiment method

In order to observe experimentally how the combustion mode is changed by jet impingement, a burner of 380KW capacity which can change collision angle of impinging jets and oxygen flow rate simultaneously was designed on the pilot scale as shown in Fig. 1. The impinging angles are set to 0°, 10°, 15° and oxygen velocities are adjusted by changing the nozzle diameters. A water-cooled heat exchanger around each nozzle was installed to prevent heating up of oxygen and fuel flow by heat conduction and radiation of in-furnace flue gas.

![Fig. 1 Impinging jet burner (a) and jet impingement configuration (b)](image_url)

Cylindrical pilot-scale furnace whose diameter of 1.5 m and a length of 6.7 m is shown in Fig. 2 (a) and combustion control system is in Fig. 2 (b). The combustion burner is located at the center front and the outlet duct is at an upper side of the end section of the furnace. NG as fuel is supplied through city gas line, and oxygen is supplied from the
liquefied oxygen tank via the vaporizer controlled by Siemens’ PLC system. Table 1 shows the composition of NG produced in Indonesia, which mainly consists of methane.

The emission data were detected by a testo 350K which had been rigged at the middle of the outlet duct. A Testo 350K exhaust gas analyzer with an accuracy of ±0.20% was employed at outlet duct of furnace. The NO sensor with the range of 0 ~ 500 ppm was used, whose the resolution range is 0.1 ppm. The fuel and oxygen flow rate were metered using Emerson Coriolis flow meter with accuracy ±0.75% at full size.

In order to form MILD combustion by internal recirculation without preheating the reactants, the furnace is prepared to be preheated at a temperature above the spontaneous ignition temperature. The experiment conducted after preheating to the spontaneous ignition temperature of oxygen-methane, 550°C, by an extra pilot burner, which is the same process as that in the real steel industry. And same fuel nozzle was used for the pilot burner and impingement jet burner. After preheating time for around one hour, oxygen is supplied through an impinging jet nozzle.

![Image](image1.png)

Fig. 2 Pilot scale furnace of 380KW (a) and combustion control system (b)

The inner furnace temperature was traced by the R-type thermocouples in real time. The sensor diameter of R-type T/C is 0.5 mm, and the sensor is covered with alumina tube. The conventional temperature range is 0 ~ 1400 °C, and the limit of overheating is 1600°C. The temperature accuracy for the thermocouple is ±1.5°C at 0 ~ 600 °C, and 0.0025 °C at 600 ~ 1700 °C.

Optical data is the image of a digital camera. These optical data are taken by the Nikon D90 with a resolution of 12 megapixels and a shutter speed of up to 1/4000 second. Using a digital camera, the inner furnace images were photographed at a distance of 30 centimeters from the visualization quartz with 1/20 second shutter speed.

Experimental condition is listed in Table 2 and the equivalence ratio (Φ) is set to 0.91, as normal operating condition of the real heating furnace, which was calculated by O2 and CO data from a gas analyzer.

| Table 1 Component of NG (Volume %)          |          |          |
|--------------------------------------------|----------|----------|
| Methane                                    | 89.396   |          |
| Ethane                                     | 8.223    |          |
| Propane                                    | 2.342    |          |
| Nitrogen                                   | 0.039    |          |

| Table 2 Conditions                         | Case | Impinging Angle(°) | Oxygen velocity(Vox) |
|--------------------------------------------|------|--------------------|----------------------|
| 1                                          | 1    | 0°                 | 60 m/s               |
| 2                                          | 2    | 0°                 | 120 m/s              |
| 3                                          | 3    | 0°                 | 220 m/s              |
| 4                                          | 4    | 10°                | 60 m/s               |
| 5                                          | 5    | 10°                | 120 m/s              |
| 6                                          | 6    | 10°                | 220 m/s              |
| 7                                          | 7    | 15°                | 60 m/s               |
| 8                                          | 8    | 15°                | 120 m/s              |
| 9                                          | 9    | 15°                | 220 m/s              |
2.2 Numerical analysis

In order to investigate the conditions under which the oxy-fuel MILD combustion is formed, three-dimensional numerical calculation was performed using Ansys Fluent 17. Fig. 3 shows the computational domain was applied symmetrical boundary condition and only 1/2 of the computational flow field was modeled. And three-dimensional meshes were composed about 500,000 cells. The mesh structure with hexahedral grids of the axial (z) and the radial (x) direction is shown in Fig. 3(b). Total mesh number was changed to 300,000, 500,000 and 1,000,000 respectively to know the independence of mesh. In the case of 300,000 grids, the interval between cells was so rough that the converged result could not be obtained. In case of 500,000 and 1 million, the temperature profiles at the center line and the radial direction on impinging point are approximately same, as shown in Fig. 4 so that the number of meshes was set to 500,000 due to a benefit of computation time. For turbulent flow calculation, a three-dimensional RANS method was employed, and a continuous equation, a momentum conservation equation, and a chemical species conservation equation were used. Realizable K - ε model is used for turbulent transport modeling and the P1 model is used for the radiation model. To describe the interaction of turbulence and chemical reaction, the EDC (Eddy Dissipation Concept) known to simulate MILD combustion properly is applied. GRI-1.2 reduced mechanism composed of 19 chemical species and 84 chemical reaction stages was used for chemical reaction. GRI-1.2 reduced mechanism composed of 19 chemical species and 84 chemical reaction stages was used for chemical reaction. The mechanism was originally developed for CH₄/Air combustion under standard conditions and it was not developed for oxy-fuel and MILD combustion. However, Mardani has showed that the mechanism can reasonably reproduce the distributions of temperature as well as major combustion related species such as CO, OH or CH₃O in the oxy-fuel MILD combustion fueled CH₄/H₂. Therefore, it can be considered that using GRI-mech 1.2 is reasonable for CFD in this research.

![Schematic of computational domain](image)

Fig. 3 Schematic of computational domain (a) and mesh structure (b)

The Pilot scale furnace modeled for this study has a capacity of about 380KW capacity which is almost same heating level in the soaking section of walking-beam heating furnace. The oxygen and fuel reactants are supplied all at room temperature (300K), and the flow rate of the supplied fuel was fixed at 30 m/s equivalent to 380KW heating capacity. The influence on MILD combustion formation by changing the oxygen velocity and injection angle of oxygen jets were numerically analyzed through the internal recirculation flow rate, the spatial temperature and concentration distribution and the dilution degree of oxygen jet by burnt gas. By analyzing numerical results, formation conditions of MILD combustion are defined as D₄ and Reₐ. And the validation check was done by comparing the numerical results and experimental data using a pilot-scale furnace.
3. Results and Discussions

3.1 Dilution effects by flow velocity

In the numerical simulation, influences of the flow velocity of oxygen and oxygen injection angle on the formation of MILD combustion were investigated. The internal recirculation rate was calculated by changing the oxygen jet velocity. Fig. 5 shows the internal recirculation ratio \( K_v \) defined as a ratio of recirculated flue gas mass flow over reactant mass flow in Eq. (1) by changing oxygen velocity from 60 m/s to 220 m/s.

\[
K_v(Z) = \frac{\dot{M}_E(Z)}{\dot{M}_F + \dot{M}_O}
\]  

(1)

Where \( \dot{M}_E(Z) \) is the mass flow rate returning to nozzle direction and \( \dot{M}_F + \dot{M}_O \) is the supplied mass flow rate of oxygen and fuel. In the Eq. (1), the mass flow rate which was the direction to the nozzle, was calculated on the plane that the intervals was 0.1 m in the axial direction. First, the planes were clipped which had negative velocity vector. And then the mass flow rate were calculated the average.

As shown in figure, the recirculation ratio increases as the oxygen velocity changes from 60 m/s to 220 m/s, enhancing the dilution of oxygen. The peak point of \( K_v \) is observed to move upward with increasing oxygen velocity, which tends to make dilution of oxygen more effectively. \( K_v \) in Fig. 5 has normally larger value compared to \( K_v \) using air as oxidant at the same equivalence ratio because there is no \( N_2 \) in oxygen supply.

In order to analyze the influence of increase of \( K_v \) on the dilution of the oxygen jet, Fig. 6 represents oxygen mass fraction along the oxygen jet axis with increasing the oxygen flow velocity. It is plotted from the nozzle inlet to the position of 1m with highest recirculation as shown in the figure.

As the oxygen velocity increases, the oxygen mass fraction along the oxygen jet axis decreases due to the stronger entrainment rate by oxygen jet. This means that oxygen jet is highly diluted by burnt gas at high oxygen velocity. The oxygen mass fraction is changed from about 0.85 to 0.5 or less as the oxygen velocity increases from 60 m/s to 120 m/s at impingement point of 0.25 m away from fuel jet nozzle. Above phenomena indicate that increase of oxygen velocity...
and impingement of oxygen and fuel seem to make a favorable condition to the formation of MILD combustion which needs higher dilution of oxygen by burnt gas.

Fig. 6 Axial distribution of oxygen mass fraction with increasing oxygen jet velocity

Fig. 7 showed the OH radical distribution (left side) and temperature (right side) inside combustor at different oxygen flow velocity. As oxygen velocity increases from 60 m/s to 220 m/s, it can be confirmed that the peak temperature becomes low by 200 K and the high temperature region above 1800 K is reduced resulting to more uniform temperature distribution. Since these temperature distributions are closely related to the OH radical distribution which is normally apparent in the high-temperature reaction region, the OH radical distribution also shows similar distribution as temperature. Especially at the oxygen flow velocity of 220 m/s, it can be seen that the temperature zone higher than the thermal NO\textsubscript{X} threshold of 1800 K temperature is almost disappeared and the temperatures are uniformly distributed indicating possibility of MILD combustion formation. In this chapter, the figures used the data where the flow velocity changed at the same impinging angles. These are cases of 0° without impinging method for comparing jet velocity characteristics.

Fig. 7 Contour of OH-radical (left side) and Temperature (right side) at different oxygen velocity
3.2 Dilution effects by angle of jet impingement

Oxygen/fuel combustion at the same equivalence ratio ($\Phi$) should have the higher internal circulation rate by changes in the oxidant supply pattern because the momentum of the oxidant supplied is smaller than that of air combustion. In this paper, we proposed an impingement method which oxygen and fuel collide each other and enhance the mixing rate greatly. So it is very important to know the influence of the impingement angles on the internal recirculation flow rate. Fig. 8 represents the internal flow patterns by impingement jets with different impingement angles.

At the impingement angle of $0^\circ$, the core of the large recirculation flow is observed to be located at downstream compared to $10^\circ$ and $15^\circ$. As impingement angle is increased, recirculation flow is moved to upstream near to oxygen and fuel nozzle. For parallel impingement at 120 m/s velocity, a large scale recirculation flow throughout an entire combustion chamber is formed while some part of burnt gas at end of combustor is vented to the outlet duct and its remaining flow is recirculated around the core center. As the impingement angle is increased, a pair of recirculating flows core is formed symmetrically along the center line and the size of recirculation flow becomes smaller and stronger. This stronger recirculation flow is thought to induce the higher dilution of oxygen and fuel jets. To confirm the effect of the impinging angle on the oxygen dilution, the central line of the supplied oxygen jet was defined as $\Psi$. And the $\Psi$ in the parallel and impinging jet are each shown in Fig. 9. Additionally, to know the degree of dilution of oxygen jet by high jet momentum, oxygen mass fraction (a) and CO$_2$ (b) as burnt gas along the jet axis are presented in Fig. 10. Fig. 10 (a) shows that oxygen mass fraction at 0.05m from oxidant nozzles is dropped from 0.96 to 0.7 as impingement is changed from $0^\circ$ to $15^\circ$ showing the effect of the jet impingement on dilution of oxygen jet. It is apparent from Fig. 10 (b) that the CO$_2$ mass fraction along the oxygen jet axis is increased with increasing the impingement angle.

Fig. 8 Streamline of flow fields on central section by oxygen jet of 120 m/s at different impingement angles
For the impingement conditions of 10° and 15°, the impingement positions are 0.25 m and 0.40 m respectively so that the dilution by burnt gas starts at different positions as shown in Fig. 9. As the impinging angle increases from 0° to 10° and 15° at the same oxygen flow rate, the internal recirculation flow moves toward the nozzle due to moving impingement point and oxygen jet was more easily diluted due to impingement of oxygen and fuel jet, which makes more favorable flow conditions for formation of MILD combustion.

3.3 Identification of MILD combustion by Damköhler and Turbulent Reynolds number

Based on the numerical results, it is very important to define the MILD combustion rigorously. In this paper, $D_a$ and $Re_t$ were used as parameters for the determination of formation of MILD combustion. Here $D_a$ is defined as the ratio of flow time scale and chemical time scale as expressed in Eq. (2),(3) and turbulent Reynolds number is given in Eq. (4) (Mardani et al., 2010; Bao, 2017).

$$D_a (\text{Turbulent Damköhler number}) = \left(\frac{\nu_t}{\epsilon}\right)^{1/2}$$  \hspace{1cm} (2)

The chemical reaction rate constant $\equiv C_r$

$$C_r = \frac{\text{Maximum Arrhenius rate of reactions}}{\rho} \hspace{1cm} (1 < i < 84)$$  \hspace{1cm} (3)

$$Re_t (\text{Turbulent Reynolds number}) = \frac{\nu_t^2}{\nu\epsilon}$$  \hspace{1cm} (4)

$$\mu_t = \frac{pC_t}{\epsilon}$$  \hspace{1cm} (5)

$$\nu_t = \frac{\mu_t}{\rho}$$  \hspace{1cm} (6)
Where $\nu$ is kinematic viscosity ($m^2/s$), $\varepsilon$ is the local turbulent dissipation rate ($m^2/s^3$), $k$ is the turbulent kinetic energy ($m^2/s^2$), $\rho$ is the local mixture density ($kg/m^3$), and $C_r$ is a local parameter which defined as the maximum of chemical reaction rate constant among 84 reactions of GRI-1.2 reduced mechanism. Eq. (5), (6), (7), (8) are the definition of each symbols. The value of the symbol used in the calculation was taken as the mass-averaged data in the generation region of the OH radical, which is a typical region of the high-temperature reaction.

Abraham et al. classified turbulent combustion regime into three regions defined as $D_a$ and $Re_t$. In this regime, it is known that MILD combustion can be defined as distributed regime of $D_a < 1$ and $Re_t < 10,000$ where reaction zones are spatially distributed (Abraham et al., 1985). Fig. 11 shows a relation of $D_a$ and $Re_t$ at different impingement angles under the oxygen velocity condition of 120 m/s.

As shown in Fig. 11(a), $D_a$ at 120 m/s approaches 1 as the impingement angle is changed from 0° to 15°. This means that the enhanced mixing of oxygen and fuel by impingement jet and dilution with burnt gas is likely to make the combustion regime to move to $D_a < 1$ defined as the MILD combustion regime. And at the condition of $V_{oxy}=220$ m/s, numerical results shows that $D_a$ is less than 1 under all the impingement angles. Also, when the flow velocity increases, the value of the eddy dissipation rate among the constants of Eq. (4) increases significantly, which lead to a decrease in the $Re_t$ value, as shown Fig. 11 (b). It is thought that very high velocity of oxygen jet can entrain a large amount of burnt gas irrespectively of impingement angles. This indicates that oxygen/fuel combustion can enter the MILD region irrespective of the impingement angle at a high oxygen flow rate above a certain level.

3.4 Comparison of Experiment and computational result

In order to investigate the formation of oxygen-fuel MILD combustion by impingement angles and oxygen velocity, a 380KW class pilot scale industrial was fabricated and various combusion experiments were conducted under the same operating condition as numerical simulation.

The Fig. 12 is a photograph taken from the rear and side of the combustion furnace, and Fig. 13 is an axial flame image along the flow direction taken from the side of the furnace. These figures show the flame patterns at different impingement angles to find out the appearance of MILD combustion.

In Fig. 12 of images taken from the combustion chamber at oxygen velocity of 120 m/s, the normal diffusion jet flame is formed around the oxygen nozzle under parallel impingement condition. These figures show flame patterns at different impingement angles to find out the appearance of MILD combustion. As the Impinging angle is increased from 0° to 15°, the diffusion jet flame becomes somewhat opaque and shows the transitional flame pattern from diffusion jet diffusion to MILD combustion. Via increasing the impinging angle from 0 to 15, the flame moved away...
from the nozzle, and it was possible to confirm the transitional trend, which occasionally appears the type of volume combustion. This transitional flame from Fig. 12 appears to agree with the numerical results that $D_a$ is approaching to 1 with increasing impingement angle in the simulation.

Fig. 12 Image of combustion flames taken from rear side of furnace at $V_{oxy}$ of 120 m/s by different oxygen jet angles

Fig. 13 Image of MILD combustion taken from side of furnace at $V_{oxy}$ of 220 m/s by different oxygen jet angles
Fig. 13 shows the flame image taken under the condition of oxygen velocity of 220 m/s at different impingement angles (0°, 10°, 15°). It shows that almost luminous flame is disappeared and the temperature is uniformly distributed irrespectively of impingement angles as shown in the figure. These experimental images clearly support the numerical results that at the oxygen flow rate of 220 m/s, flame regime enters the MILD region satisfying conditions of $D_a < 1$ and $Re_t < 100$.

Fig. 14 shows that the NO$_X$ emission decrease when the oxygen velocity rising. It means that the MILD combustion mode has lower temperature than conventional flame. And the impinging method can achieve the reduction of NO$_X$ at MILD combustion mode. CO under all the operating conditions was measured below 40 ppm indicating the complete reaction of NG and oxygen.

![Fig. 14 Comparison of experimental NO$_X$ emissions data at different combustion mode](image)

Fig. 14 shows comparison of temperature data obtained from a numerical analysis and experimental results under the MILD combustion condition of the impinging angle 10°. The wall temperature is temperature applied to the edge of the flow field. In the combustion experiment, when the T/C is inserted inside in a furnace, the alumina insulator accumulates heat and acts as an igniter. Therefore, we tried to position the wall as close as possible to the wall, and the distance between the wall and the T/C was 5 cm. Also, the position of a numerical wall condition equated to an experimental data. The numerical result shows that the spatial temperature distribution is predicted similar to the experimental ones but temperature deviation at inlet and outlet region is a little bit high because of complex impinging flow at inlet and the interaction of exhaust gas flow with an end wall of furnace.

![Fig. 15 Temperature profile at the furnace wall compare with CFD and EXP](image)

Fig. 15 Temperature profile at the furnace wall compare with CFD and EXP
4. Conclusion

Three-dimensional numerical analysis and combustion experiments to analyze the influence of injection angle and oxygen flow rate on formation of oxygen-fuel MILD combustion were carried out and following results can be obtained.

1) For the formation of oxygen MILD combustion, jet impingement method was applied in numerical simulation to enhance the internal recirculation flow and also compensate the drawback that the momentum of oxygen becomes smaller than that of air combustion. As the impinging angle increases from 0° to 10° and 15° at the same oxygen flow rate, the internal recirculation flow moves toward the nozzle due to moving impingement point and oxygen jet was more easily diluted due to impingement of oxygen and fuel jet, which makes more favorable flow conditions for formation of MILD combustion.

2) As the flow velocity of oxygen increases, the stronger internal recirculation ratio (K_V) makes the oxygen jet more diluted leading to reduce the maximum temperature and high temperature zone inside combustor in numerical simulation. It was also found that under the condition of oxygen flow rate of 220 m/s, MILD combustion having a uniform temperature distribution below 1800K can be formed irrespectively of impingement angles showing the dominant effects of entrainment rate of high oxygen momentum jet.

3) Numerical analysis shows that the Damköhler number approaches to 1, where chemical characteristic time is comparable to flow characteristic time, as the impingement angle increases at the oxygen velocity of 120 m/s and MILD condition of D_a < 1 and Re_t < 100 was satisfied at the oxygen flow velocity of 220 m/s.

4) Transitional flame from diffusion jet flame to MILD flame at the oxygen flow velocity of 120 m/s was experimentally observed as the impingement angle increases in the combustion experiment using 380KW pilot-scale combustor. In addition, at oxygen flow velocity of 220 m/s, almost of flame fronts were disappeared and the flameless flame was formed under all the impingement angles in the experiment due to higher dilution rate by high momentum of jet. It is confirmed that above experimental flame images clearly support various numerical results which can provide valuable data for designing the oxygen MILD based furnace.

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