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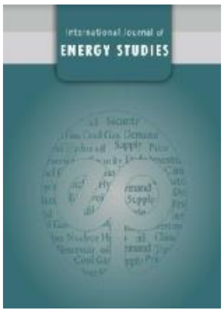

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Combustion Characteristics on Colorless Distributed Combustion (CDC) in a Cyclonic Burner

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Highlights

- Methane was combusted in a cyclonic burner
- CDC conditions were achieved with CO_2 dilution
- Ultra-low NO_X pollutant emission was obtained
- CO pollutant emission was decreased considerably

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ABSTRACT

Colorless distributed combustion (CDC) is a novel combustion method. Ultra-low NOx and CO pollutant emissions, more uniform thermal field, stable flame formation, equally temperature distribution, etc. can be provided by CDC conditions. CDC can be performed to different type of burners likewise cyclonic burner. Cyclonic burners could provide more residence time on account of intensely internal circulation compared to conventional designated burners. On the other hand CDC is attained by external recirculation. Therefore, non-premixed combustion of methane using a cyclonic burner was modelled through a commercial computational fluid dynamics (CFD) code to enable both external and internal recirculation in the study presented. In the modelings, Reynolds Stress Model that predicts accurately higher level turbulence closures was used as the turbulence model. The assumed-shape with β-function Probability Density Function non-premixed combustion and P-1 radiation models were also used as the combustion and radiation models, respectively. In order to achieve transition to CDC, CO_2 as the diluent was selected to decrease oxygen concentration in the oxidizer from 21% to 17%. The transition to CDC was reached at nearly an oxygen concentration of 17% by burning methane at an equivalence ratio of 0.83 with reducing oxygen concentration in the oxidizer by CO_2. Ultra-low NO_X is achieved for favorable conditions. Besides, CO levels was reduced substantially.

Keywords: *Colorless Distributed Combustion, Methane, Cyclonic Burner, CFD, Carbon Dioxide*

1. INTRODUCTION

Energy is the one of the main requirements to sustain modern life. Therefore energy production has considerable amount budget items in developing and developed economies. This indicates that energy is a crucial matter for human well-being.

Energy is acquired from energy sources which can be classified as conventional and renewable. Fossil fuels, one of the conventional energy sources, cause several critical consequences on the environmental balance in terms of CO_2, CO and NO_x emissions as compare with renewable sources during the operation. Having taken into account these side effects, engineers have expanded the investigations to achieve that more efficient and cleaner combustion systems design. As a result of these studies, several methods have been revealedç Some of these methods can be classified as follow: Colorless Distributed Combustion (CDC) [1-4], Moderate or Intense Low Oxygen Dilution (MILD), Flameless Oxidation [FLOX] [5-7].

When the CDC method, which has similar features with HiTAC (High Temperature Air Combustion), is evaluated by considering flame stability, noise level and pollutant emissions, the outputs emerging show that lower NOx and CO emissions, flame instability, noise level can be achieved [8]. In order to attain CDC conditions, oxygen concentration in the oxidizer is reduced. However, total oxygen amount required should remain constant as long as fuel flow rate is stable to protect stoichiometric mixing of fuel and oxidizer. Thus reaction rate is slowed down, and as a result of this, temperature distribution intensity can be more uniform. Besides, concentrated thin flame is broadened into the combustion chamber, and becomes a invisible flame. [9].

In order to reduce pollutant emissions and increase combustion efficiency, scientists have carried out several studies. In briefly, Sidey et al. have performed numerical and experimental investigations on propane [10], methane [11], dilution with CO_2 and H_2O [12] taking into account auto-ignition delay time at MILD condition. Sidey et al. has conducted numerical analysis pertaining to laminar strained non-premixed flames of methane at specific MILD conditions. Sidey has examined the prompt and thermal NOx generations in that article [13]. Li at al. numerically and experimentally investigated impact of H_2 mixing in methane on the generation of NO at MILD condition. Consequently, NO_x ratio remains steady. On the contrary, increasing of temperature caused much more thermal NO_x emissions [14]. Costa et al. improved his novel gas combustion rector. Thus, Costa has shown the effect of location and angle of inlet air on the efficiency [15].

Reference to above studies on methane combustion using a cyclonic burner was researched under colorless distributed combustion conditions dilution with CO_2. To this end, the cyclonic burner that was preferred in the study conducting under MILD conditions by Sorrentino et al. [16] was used for the higher internal recirculation rate. Then, Fluent CFD code was used to predict the temperature and the pollutant emissions levels such as NO_x and CO of methane combustion under CDC conditions dilution with CO_2.

2. MODELING DETAILS

As stated above, almost the same burner that was used in Sorrentino's study was selected for modelling [16]. The reactor is designed using Ansys design modeler and by taking into account reactor capacity as 2 kW. In this direction air flow and fuel diameters were determined along with air velocity. The view of the burner established was shown in Figure1 (isometric view) and in Figure 2 (Top view). It can be seen on the figures that fuel and oxidizer inlet sections are installed on the lateral wall. Burner outlet is placed on the top of burner as can be seen in Figure 1.

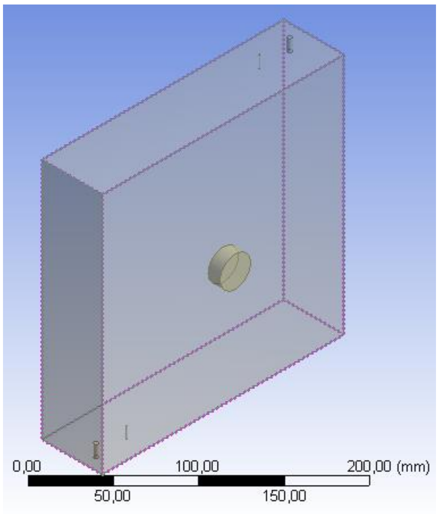

Figure 1. The isometric view of the burner

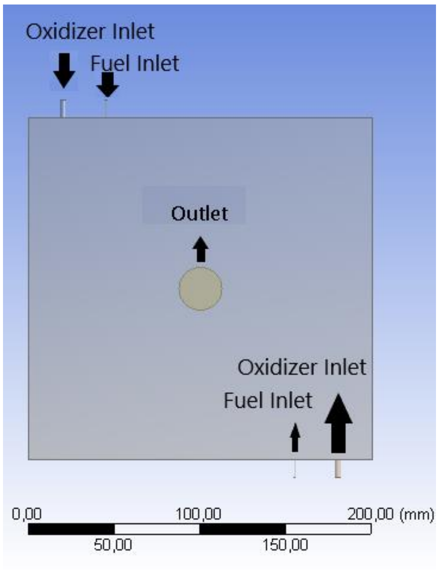

Figure 2. The top view of the burner

The fuel flow rate was specified taking into account to keep constant as a thermal power of 2 kW for all conditions studied (Table 1). Then, the fuel inlet diameter was calculated as 0.89 mm in the view of the thermal power determined. Likewise, the oxidizer inlet diameter was also calculated as 3.39 mm considering an equivalence ratio of 0.83 and the thermal power determined. Then, the all oxidizer flow rates for each condition have been calculated considering which equivalence ratios and oxygen concentrations are studied. It means the oxygen concentration in the oxidizer decreases as CO_2 diluent is introduced into the oxidizer. Also the burner outlet diameter was determined as 25 mm. The reactor height, width, and length are of 50 mm, 200 mm, 200 mm, respectively.

Table 1. Operating conditions

Equivalance Ratio	Mixture Temperature (K)	Oxygen Concentration (% by volume)
0.83	300	21%
0.83	300	20%
0.83	300	19%
0.83	300	18%
0.83	300	17%

Ansys Fluent commercial program has been used for numerical analysis of turbulence reacting flow. Modelling algorithm of flow was taken into account as steady-state and three-dimensional continuity. Energy, momentum, and species transport equations were solved iteratively. Linear pressure–strain Reynolds Stress Model (RSM) turbulence model along with non-equilibrium wall function was selected due to its higher preciseness capacity for highly swirling flows. For species transports, the assumed-shape with β-function Probability Density Function non-premixed combustion model was chosen together with inlet diffusion option. Scheme simple was determined for pressure–velocity coupling. The other constituents were determined as respectively: Pressure: Presto; Gradient: Least Square Cell-Based; Momentum and Turbulent Kinetic Energy: Second Order Upwind. Convergence criteria for each equation was selected at least 10^{-4}.

Minimum 460000 cells have been used to estimate the temperature field and pollutant emissions. More than 460000 cells have also been used for some modelings such conditions at lower oxygen concentrations required using more cells to reach convergence criteria. In this study, for NO_x pollutant emission prediction, Ansys Fluent post-processor was preferred. As it is well-known that there are three NO_x formation mechanisms that are called as thermal (oxidation of nitrogen in the air at high temperature), prompt (which is produced at fuel-rich zones due to hydrocarbon fuel separation reactions) and fuel-NO_x. However, for this study, thermal and prompt NO_X mechanisms have been activated to predict NO_x levels. Fuel NO_x has not been activated as methane has not any fuel-bound nitrogen.

3. RESULTS AND DISCUSSION

3.1. Model Validation

In order to accept that all modeling results are favorable, validation with experimental data is very critical. To this end, some modelings have been carried out to compare and validate with the experimental data conducted in the study reported by Sorrentino et al. [16]. They burned $C_3H_8/O_2/N_2$ mixture with highly preheated air and obtained some experimental results. Consequently, the numerical results predicted and the data measured are compared each other in Figure 3. It is understood from Figure 3, the numerical results are in good agreement with the experimental data. Experimental temperature differences have been given as 120 K, 160K, 140K. Numerical temperature differences have been predicted as 59 K, 212K, 148K. The calculated reactor max temperature error ratios have been found as -5,24%, 4,32%, 0,68% according to C/O ratio 0,3/ 0,4/ 0,6 respectively. So, it can be said that further modeling for this burner can be implemented in terms of preciseness.

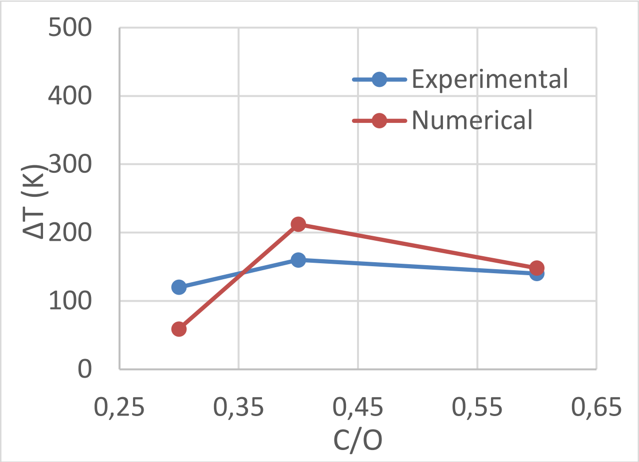

Figure 3. Model validation

3.2. The effect of oxygen concentration with carbon dioxide dilution on temperature field

Figures 4 to 8 show the effect of oxygen concentration on the temperature field inside the burner. The maximum temperature level has been estimated as around 2040 K at an oxygen concentration of 21%. Then, the maximum temperature values reduced as the oxygen concentration in the oxidizer was decreased by introducing CO_2 diluent into the oxidizer. The maximum temperature values for each oxygen concentration have been predicted almost 1980 K, 1950 K, 1910 K, 1850 K at oxygen concentrations of 20%, 19%, 18%, 17%, respectively. As for temperature distributions, it can be said that high temperature zones replaced in the burner with being reduced the oxygen concentration in the oxidizer. This is because of higher flow rates and lower flame speeds at lower oxygen concentrations. However, for the cyclonic burner, CDC conditions did not change considerably temperature field even if a little more uniform thermal field was obtained inside the burner. After an oxygen concentration of 17%, the burner was not continued to model as the NO_x values predicted (the results are presented in 3.3. section) decreased below 2 ppm, which is considered CDC is achieved.

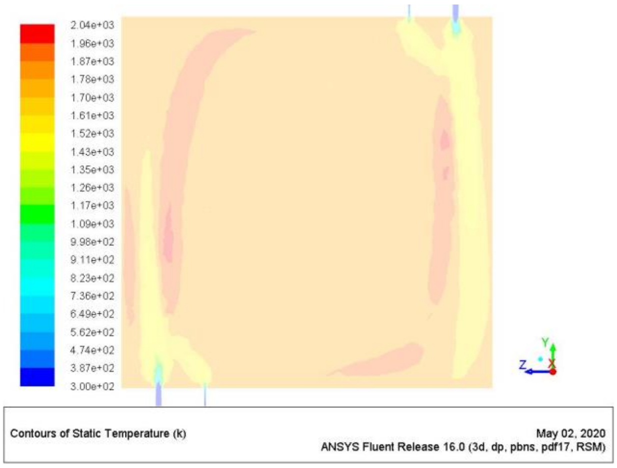

Figure 4. Temperature distributions at oxygen concentration of 21%

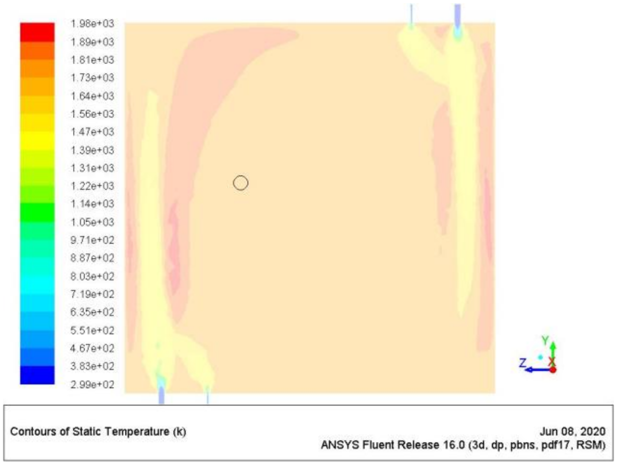

Figure 5. Temperature distributions at oxygen concentration of 20%

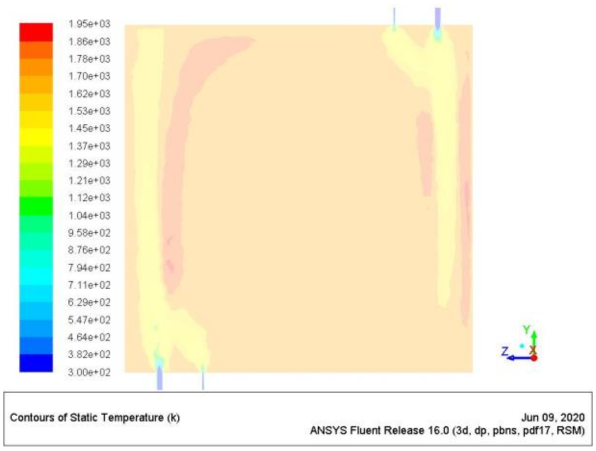

Figure 6. Temperature distributions at oxygen concentration of 19%

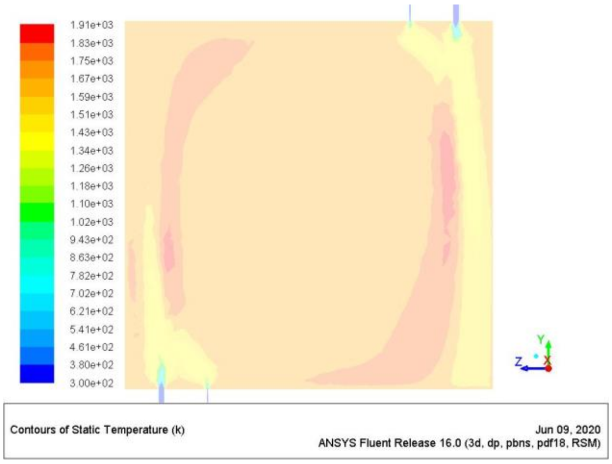

Figure 7. Temperature distributions at oxygen concentration of 18%

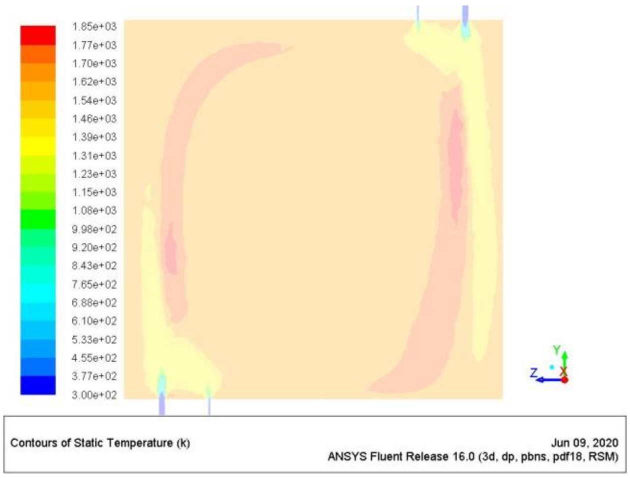

Figure 8. Temperature distributions at oxygen concentration of 17%

The temperature profiles at different oxygen concentrations along the centerline of the burner are shown in Figure 9. When it is looked at in Figure 9, the first conclusion is that the temperature levels decreased gradually as the oxygen concentration was decreased. The other important conclusion here is to reveal a more uniform thermal field was obtained under CDC. In particular, it is concluded that the temperature differences between the values close to the walls and at the burner center are not too different. Therefore, in terms of a more uniform thermal field, it can be said that CDC was achieved.

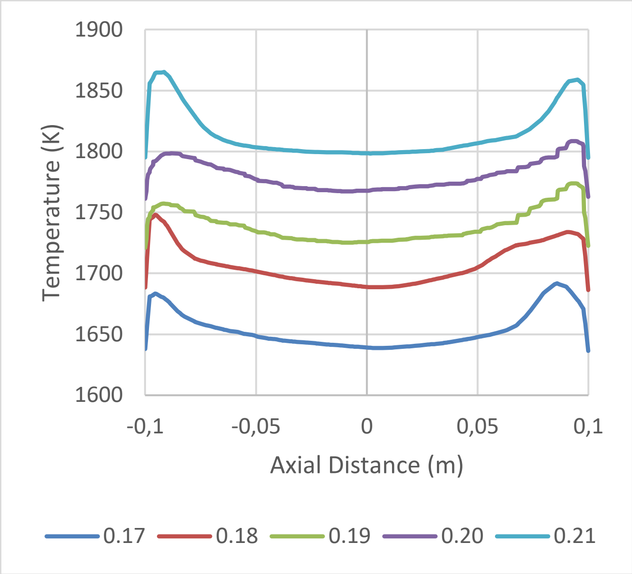

Figure 9. The temperature profiles along the centerline of the burner at different oxygen concentrations

3.3. Pollutant Emissions

In order to understand the transition to CDC, the effect of reduced oxygen concentration on pollutant emissions such as NO_x and CO are presented here. The NO_x profiles at different oxygen concentrations and equivalence ratios along the diameter of the burner outlet are shown in Figure 10. Moreover, the mean NO_x and CO levels estimated at the burner outlet are given in Figure 11 and Figure 12. According to Figure 11, it can be said that reducing oxygen concentration affected substantially the NO_x levels predicted. It can be seen from the Figure the NO_x levels predicted reduced drastically as the oxygen concentration in the oxidizer was reduced. Such that, at an oxygen concentration of 17%, the NO_x value predicted is of around 1.3 ppm, which suggests that CDC is achieved in terms of ultra-low NO_x level.

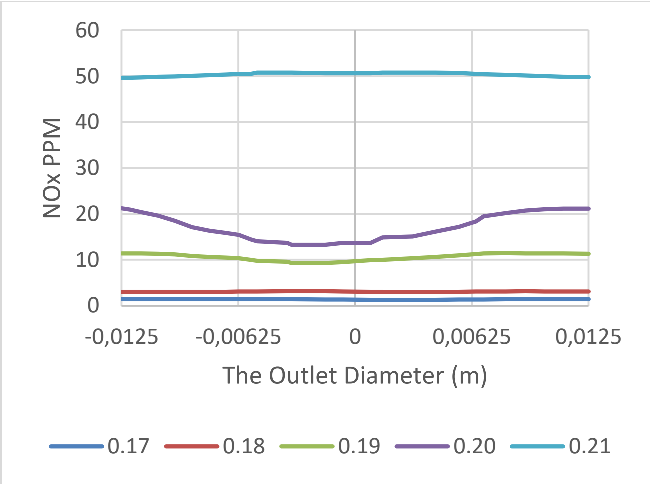

Figure 10. The NO_x profiles along the diameter of the burner outlet at different oxygen concentrations

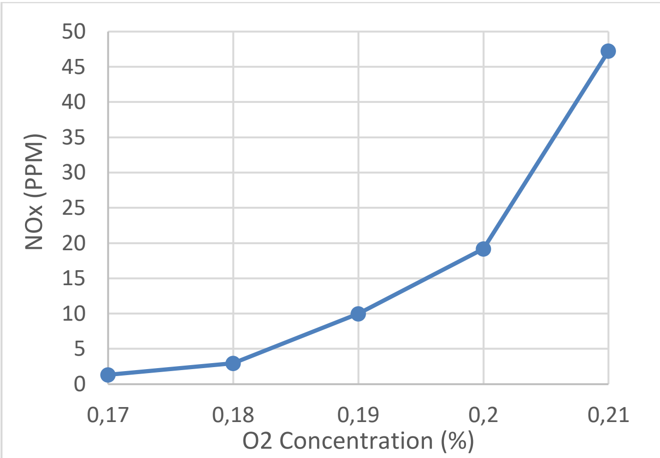

Figure 11. The effect of oxygen concentration on NO_x emission levels at the burner outlet

Figure 11 and Figure 12 illustrate the impact of oxygen concentration on mean NO_x and CO pollutant emissions at the burner outlet. Both NO_x and CO pollutant emission have reducing trend significantly with reducing the oxygen concentration and increasing the carbon monoxide concentration.

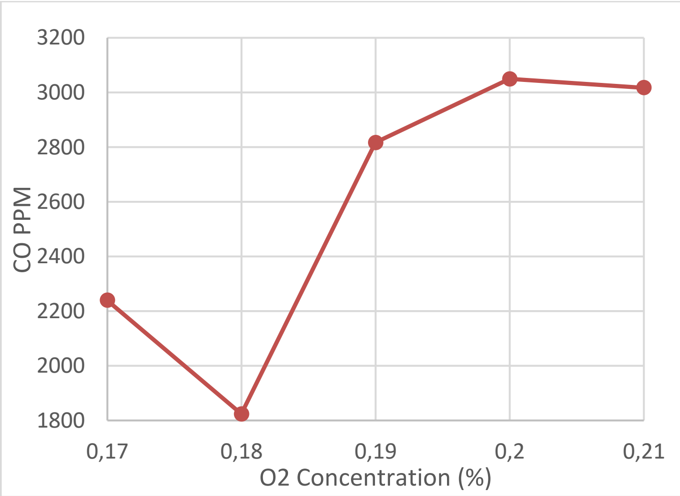

Figure 12. The effect of oxygen concentration on CO emission levels at the burner outlet

4. CONCLUSIONS

The non-premixed combustion of methane using a cyclonic burner was modeled by Ansys Fluent commercial code to perform CDC conditions in the present study. Reynolds Stress turbulence model, the assumed-shape with β-function Probability Density Function non-premixed combustion model, and P-1 radiation model were used to predict temperature field, and pollutant emissions such as NO_x and CO. In order to simulate CDC, CO_2 as the diluent was introduced into the oxidizer to reduce the oxygen concentration in the oxidizer from 21% to 17%. It has been concluded that the transition to CDC was achieved at around an oxygen concentration of 17% when methane was combusted at an equivalence ratio of 0.83. As for the conclusion of pollutant emissions, it can be concluded reducing the oxygen concentration affected considerably the NO_x levels predicted (1,3 / 2,93 / 9,96 / 19,16 / 47,24 ppm at 0,17/ 0,18/ 0,19/ 0,20/ 0,21 of O_2 concentrations, respectively (ultra-low NO_x level has been predicted as around 1.3 ppm). CO levels have also been predicted from around 3000 ppm to less than 1800 ppm at the oxygen concentration of 21% to 17% under CDC due to the high internal recirculation capability of the cyclonic burner. Therefore, it can be said cyclonic burners providing high internal recirculation can be used in practical applications such as gas turbines under CDC conditions to obtain a more uniform thermal field and ultra-low NO_x and less CO pollutant emissions. For the future studies, it can be recommended oxidizer and fuel inlets configurations can be modified to be placed on different wall surfaces. In this way, fuel and oxidizer could be mixed to take place more effecient combustion process.

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Declaration of Ethical Standards

The authors of this paper declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

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