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Numerical study of inlet air conditions on methane flameless combustion characteristics

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Numerical study of inlet air conditions on methane flameless combustion characteristics

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Abstract. The current study investigates the influence of inlet air momentum and temperature for flameless characteristics. Three-dimensional computations were implemented by ANSYS FLUENT. A small-scale experimental combustor geometry was used for validation study. Turbulence modelling was performed by RNG k- Ɛ model and the GRI-Eddy Dissipation Concept (GRI-EDC) model was used for the combustion modelling. The influence of inlet air velocity was investigated through using different air jet diameters at constant flow rate. Five different air jet diameters (4,6,8,10 and 12 mm) were studied. It was found that decreasing air jet diameter leads to an increase in the exhaust gas recirculation which reserve in mixture dilution (low O_2 content mixture) subsequently, the reaction rate decreases which support the flameless mode creation. Also, this recirculated gas participates in heating up of fresh reactants which make the mixture tends to complete combustion. The influence of combustion air preheating temperature on NO and CO emissions were studied. CO and NO concentration were decreased with reducing the temperature of inlet preheated combustion air.

Keywords: Flameless combustion, Emissions, Combustor design, Mixing

1. Introduction

Flameless combustion was identified during the experimental work of Wünning, J. G [1] and then employed in different industrial applications to decrease NOx emissions and perform high combustion efficiency. Flameless combustion regime is characterized by invisible flame boundary, low noise and more uniform temperature in comparison to conventional flames. Flameless combustion has a lot of different names and expressions in reviewed articles. Some of researches called the flameless phenomenon as HiTAC [2], CDC [3,4], FLOX [1,5] and MILD combustion [6,7].

In flameless mode, the mixture shall be diluted by internal recirculated combustion products. Therefore, fuel and combustion air commonly injected with high velocity into the furnace. Subsequently, combustion products entrained by high velocity air jets before the burning. Fast dilution of reactants requires a high turbulence intensity of recirculated combustion products [8]. As a result of recirculated burnt gases, oxygen concentration in combustion air quickly decreases (low O_2 mole fraction concentration). Consequently, reaction time increases [8] and reaction rate decreases [9] which may be described as low Damköhler number reaction (Da<<<1) [10]. Damköhler number represent the ratio between mixing time to combustion time [8]. The decrease in reaction rate leads to the combustion occurs in a distributed reaction zone [11,12]. Consequently, combustion zone spreads out along the whole furnace [8] and described as a large flame volume [13]. In contrast, traditional visible flames

combustion zone concentrated next to the burner tip due to sufficient high O_2 concentration which increases the reaction rate. Dilution of reactants and low Damköhler number generates an increase in the homogenization of furnace temperature contours [8]. Also, mixture dilution causes a decrease in adiabatic flame temperature [11,12]. This, in turn, leads to uniform axial temperature, avoiding of temperature peaks and prevention of a hot spot formation in furnace [8]. Flame boundary and luminosity disappeared in flameless combustion due to the oxidation of high carbonaceous species [14,15] consequently, soot formation can be negligible [16]. Exhaust gas which recirculated (diluents) contains CO_2 and H_2o and converts to different radical compounds such as CO, OH which help in the oxidation process [14,15]. The exhaust gas recirculation normally exists in both conventional flame and flameless, but the difference is that the recirculated percentage in flameless shall be large [16].
Preheating the combustion air plays an important role in flameless combustion [11,17-21]. Air preheating can be achieved either by electric heater [9], or by waste heat recovery applications. Recuperator technology can be used for air preheating process. Some applications [22] reducing energy for electrical heating system by heat recovery through using stack exhaust gases to raise the air temperature and then entering an auxiliary electrical heating system which raised the air to higher temperature. Also, heat recovery regenerators [23,24] and regenerative burners [25] are utilized to raise the combustion air temperature. So, the demand of flameless combustion increased due to the growing trend of high fuel price and because of its high combustion efficiency.
Most of previous works [26-30] focuses on improvement the mixing in reaction zone. Another articles [31-35] on flameless combustion were depended on heating the combustion air temperature to achieve the autoignition temperature, hence ensure the complete combustion. Some of previous studies [36-38] showed that flameless regime may be generated without raising the air temperature. Rottier et al. [35] examined experimentally the influence of inlet air temperature on flameless combustion characteristics. Veríssimo et. al. [39] presented experiments in a small-scale flameless combustor using different air jet velocity, and found that raising inlet air velocity leads to an increase in reactants dilution with recirculated hot combustion products.
This paper presents a theoretical investigation for the effect of air inlet velocity on mixing and recirculation at the exit of the burner. Also, this research investigates numerically the effect of preheated air temperature on flameless regime emissions. Different values of inlet air temperature are ranging from ambient air to 1173 K were studied.

2. Computational models
The current research was based on the geometry of a lab flameless combustor which presented by experimental study of Verissimo et al. [29,39]. This combustor consists of 100 mm diameter quartz cylinder have a length of 340 mm and steel tapered cylinder with angle 15° and length 150 mm were used at the combustor outlet. Figure. 1 shows the flameless burner configuration which consists of 5 mm radius for central inlet air and 16 fuel nozzles created on a circle with radius 15 mm. Methane fuel was used at ambient temperature and the combustion air temperature was heated to 973 K in these experiments [29,39]. It is cleared that the geometry has a symmetrical configuration subsequently, only a quarter section of the configuration was considered to decrease the CFD running time. a 3-D grid consists of 743,042 cells was generated using ANSYS mesh as shown in Figure. 2 where the average values of both mesh element quality and skewness were 0.689 and 4.5e-2 respectively. FLUENT 19.0 was implemented in the present work. RNG k- Ɛ model was employed for the RANS turbulence modelling. Flameless combustion described with low reaction rate which leads to large reaction zone as explained in the introduction section. Therefore, Eddy Dissipation Model (EDM) cannot used for flameless combustion. Eddy Dissipation Concept (EDC) model is an updated form of EDM and created to treat with slow chemical reaction rate. EDC model cannot solve all chemical species so, it was a mandatory to use the detailed mechanism GRI-MECH 3.0 with EDC model. Then the RNG k- Ɛ turbulence model and the GRI-EDC models were selected in the present work to simulate the combustion process. Flameless combustion can be considered a complete combustion subsequently, most of exhaust gas consists of CO_2 and H_2O and soot formation can be negligible. Therefore, the

reaction products can be considered a non-luminous species which reduces the radiation effect so, thermal radiation modelling can be negligible and wasn't taken into account in the current work. All properties of the current study can be summarized in Table 1. Setting of boundary conditions and operating variables were shown in Figure. 3 and their values were presented in Table 2. The solution was considered to be converged when the residuals of each parameter decrease to the values which reported in Table 3.

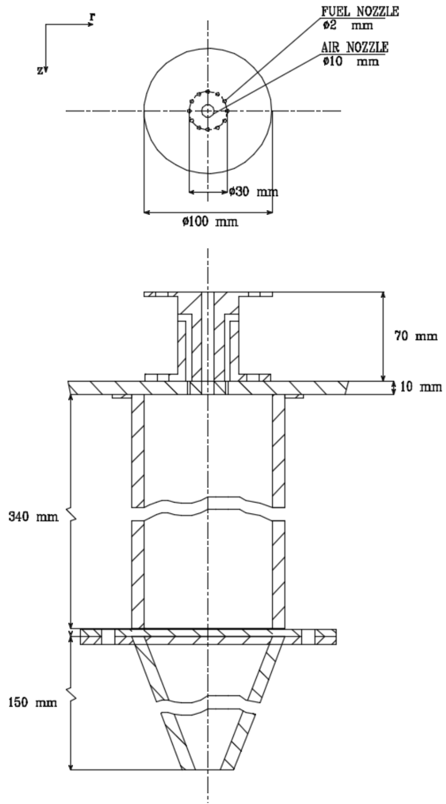

Figure. 1 combustor and burner dimensions (Verissimo et al. [29,39])

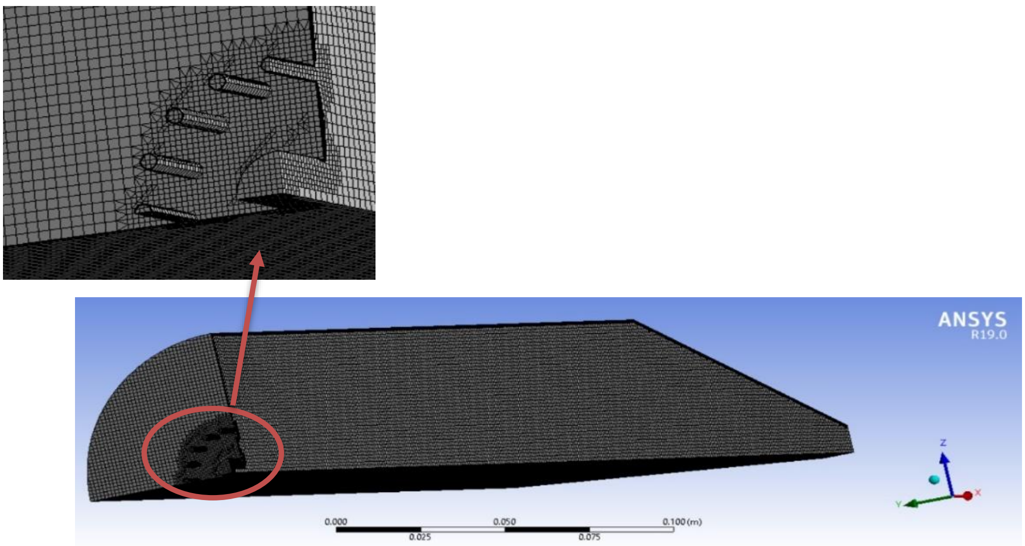

Figure. 2 Computational grids

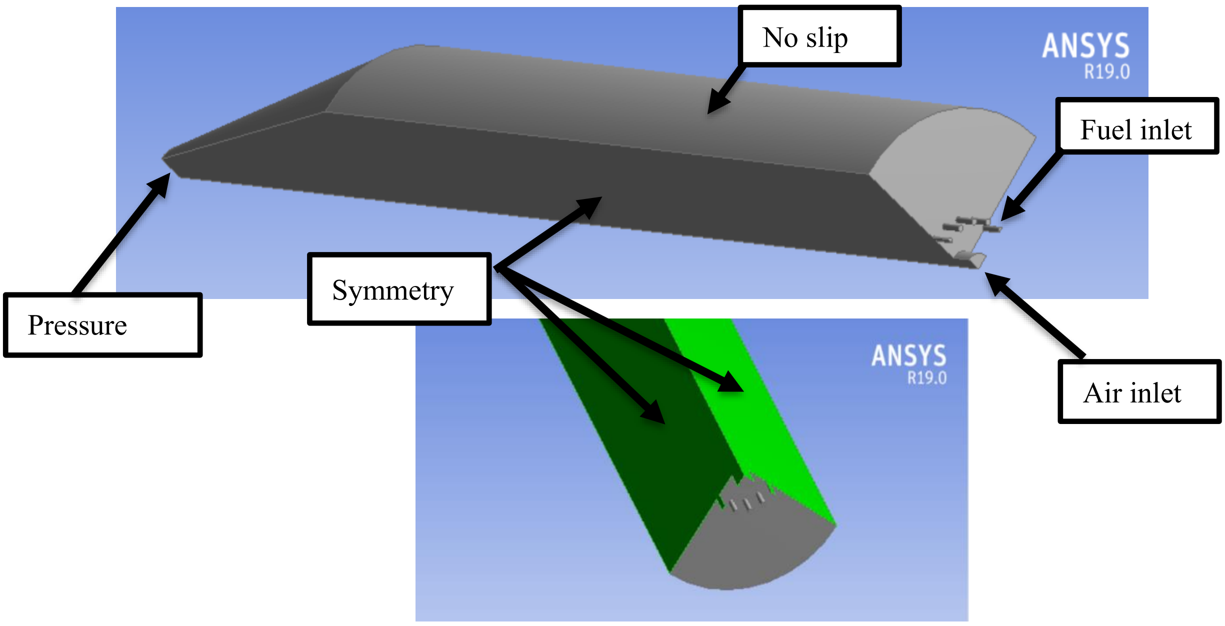

Figure. 3 Operating boundary conditions

Table 1 Simulation specifications

Viscous model	RNG K-Ɛ
Near wall modelling	Standard wall function
Radiation model	negligible
Combustion model	Species transport model
Mixture properties	Methane-air
Turbulence chemistry interaction	EDC&GRI 3.0
Reaction	Volumetric

Table 2 Simulation boundary conditions

Oxidizer (Air) inlet	Velocity	Experimental case =157.5	m/s
	Gage pressure	0	Pa
	Temperature	Experimental case= 973	K
	Hydraulic diameter	10	mm
	Oxygen concentration	0.23	
	Turbulence intensity	20	%
Fuel inlet (Methane)	Velocity	6.1	m/s
	Gage pressure	0	Pa
	Temperature	300	K
	Hydraulic diameter	2	mm
	Ch4 concentration	1	
	Turbulence intensity	20	%
Stationary wall (combustor)	Wall slip	Non-slip	
	Thermal condition	Fixed temperature	
	Temperature	1400	K
Pressure outlet	Hydraulic diameter	196	mm
	Gage pressure	0	Pa
	Turbulence intensity	10%	

Table 3 Convergence Criteria

Continuity	XYZ - VELOCITY	ENERGY	K-Ɛ	MAJOR SPECIES CH_4,O_2,CO_2,CO	OTHER SPECIES
1E-3	1E-6	1E-6	1E-5	1E-6	1E-4

3 Results and Discussion

Numerical analysis helps in understanding flow characteristics and combustion products recirculation in flameless combustor. The experimental results of Verissimo et al. [29,39] were used for validation study. Figure. 4 shows a good agreement between theoretical and experimental results. Figure. 5 presents axial velocity contours at various values of air nozzle diameter subsequently, different inlet air velocity. It is shown that decreasing the air jet diameter leads to increasing air velocity up to large values which able to create reverse flow. The revers flow pattern is cleared from distributions of negative axial velocity which appeared with decreasing the air nozzle diameter (d_{air}) from 12 mm to 10 mm. The values of negative axial velocity increased more and more at the smallest air jet diameters which means a big quantity of combustion products is recirculated as presented in Figure. 6. Increasing the exhaust gas recirculation helps in mixture dilution (mixture with low O_2 content as shown in Figure. 7) subsequently, the reaction rate decreases which support the flameless mode creation. Also, this recirculated gas participates in heating up of fresh reactants which make the mixture tends to complete combustion hence, most of emissions consists of CO_2 and H_2O which known as a non-luminous gas and interprets the disappearance of flame boundary.

The preheated combustion air temperatures were progressively decreased from 900^0c to atmosphere air temperature. the mean mole fraction of CO and NO_x were presented in Figure. 8 and Figure. 9. It is cleared that raising the combustion air temperature generates an increase in CO and NO concentration due to the expected dissociation which reveals with high temperature.

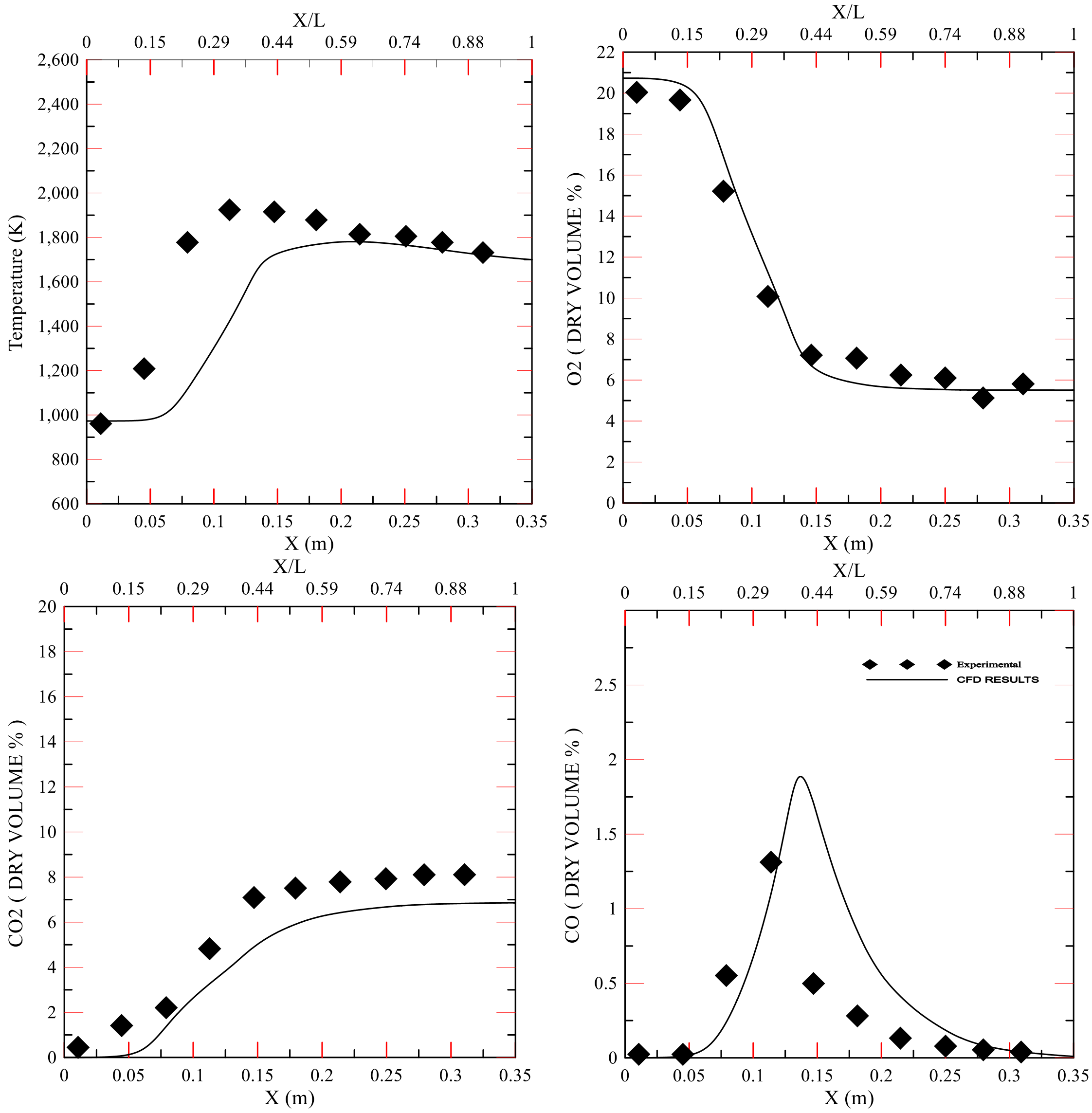

Figure. 4 Experimental and predicted axial results for mean temperature, O_2, CO_2 and CO mole fraction

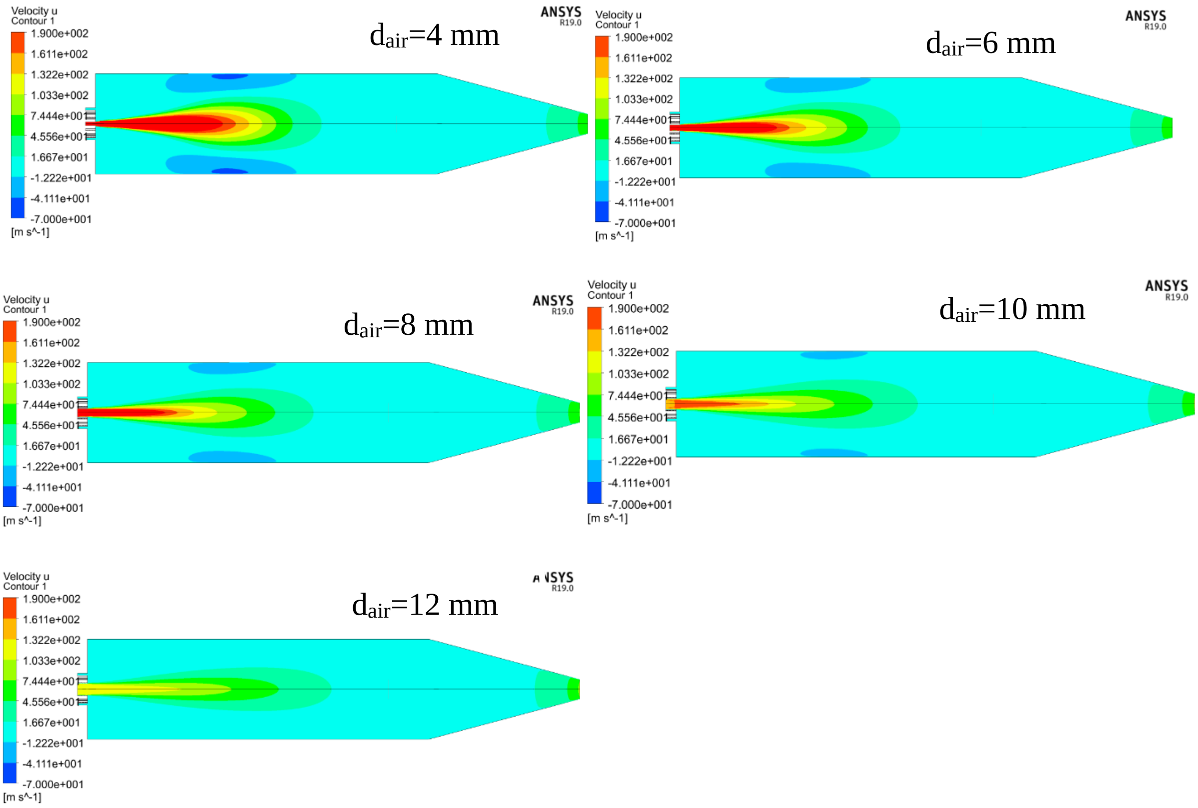

Figure. 5 Axial velocity contours at different values of air nozzle diameter (different inlet air velocity)

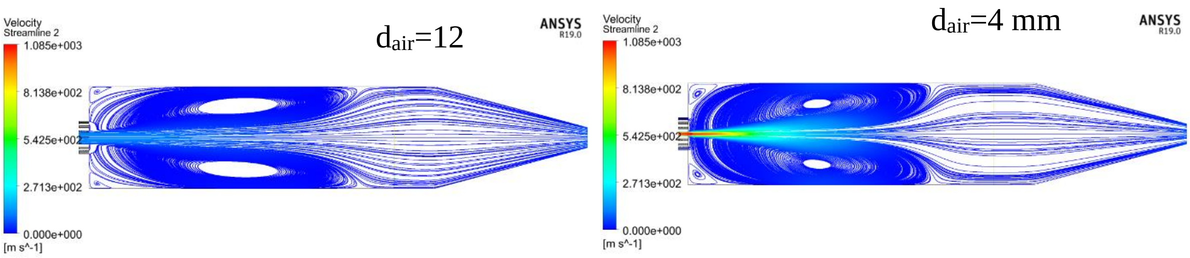

Figure. 6 Predicted flow stream lines through the combustor symmetry plane for different air nozzle diameters

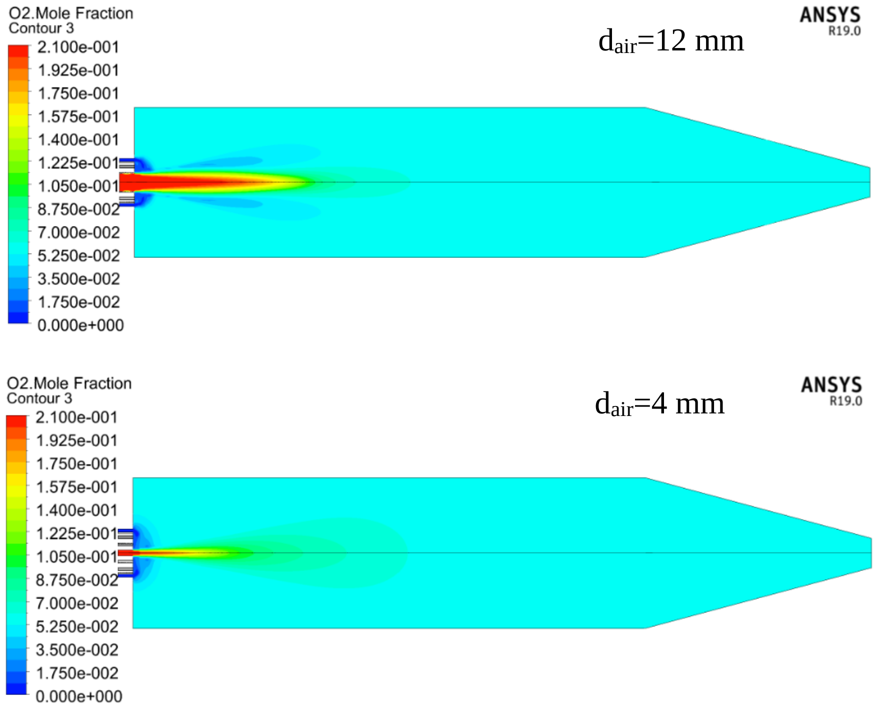

Figure. 7 O_2 mole fraction contours for reducing inlet air diameter from 12 to 4 mm

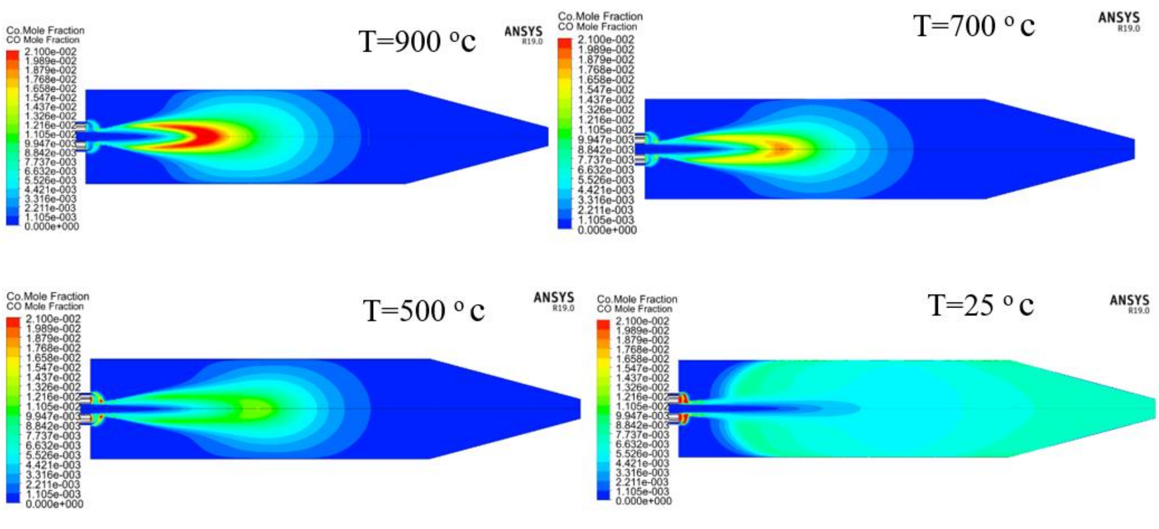

Figure.8 Predicted CO mole fraction contours through the combustor symmetry plane

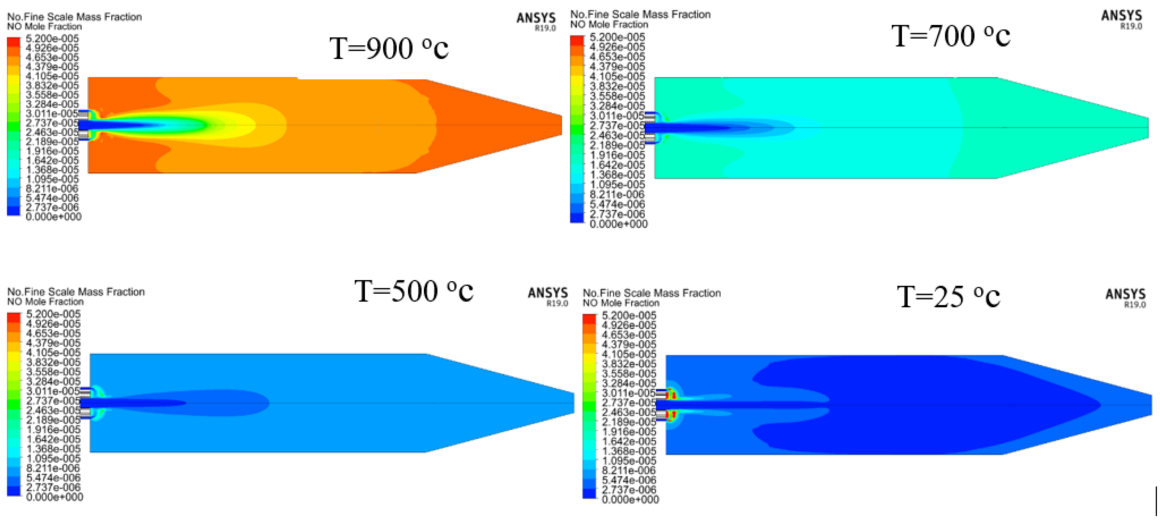

Figure. 9 Predicted NO contours through the combustor symmetry plane

4 Conclusion

In this work a numerical study of flameless combustor was presented. Turbulence modelling was performed by RNG k- Ɛ model and the GRI-Eddy Dissipation Concept (GRI-EDC) model was used for the combustion modelling. Generally, GRI-EDC model shows a good agreement with the experimental measurements. Influence of several inlet air jet velocities were investigated. It was concluded that exhaust gas recirculation ratio increased with increasing combustion air velocity. Larger dilution of the mixture was achieved with increasing air velocity which reduces the reaction rate and support the flameless mode generation. The influence of combustion air temperature on CO and NO emissions was studied. It was found that these emissions increase due to raising combustion air temperature.

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