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# Investigation of the Effects of Temperature, Mass Flow Rate of the Injected Fuel, Pore Diameter, Porosity and Ambient Pressure on the Amount of Pollutants in the Combustion Chamber

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*Environmental pollutants such as soot, nitrogen oxides, and carbon monoxide are the main demerits of fossil fuels. Therefore, it is imperative to control the air pollutants in order to provide a clean and pleasant environment. In the present study, the effects of temperature, mass flow rate of the injected fuel, pore diameter, porosity and ambient pressure on the amount of pollutants are investigated in the combustion chamber. The combustion process is numerically simulated by employing Species Model at species transport mode of operation. Discrete Phase Model is used to predict flow field behavior by considering the interaction between liquid and gas phases. Also, the flow is simulated under turbulent regime with the diffusive flame in the combustion process. Results show that increasing the heat transfer in porous medium leads to the decrease in the gas temperature and* $NO_X$ *formation. The production of unburnt hydrocarbon species like carbon monoxide decreases due to a better pre-heating process in the porous medium. Increasing the diameter of pores slightly reduces the amount of carbon monoxide, while the amount of nitrogen monoxide surges up.*

*Keywords:* Diffusive flame, Urea solution, Pollutants, Pore diameter, Porosity.

## 1 Introduction

Pollutants generation and emission along with the growing fuel consumption in metropolitan areas have been considered as serious issues. Due to the rapid growth of urbanization and industrialization, air pollution has become one of the primary environmental problems in many industrial megacities, leading to a sharp decrease in the quality of fresh air. Based on the report released by the World Health Organization (WHO), more than 300 million people die each year by breathing polluted air [1]. Air pollutants such as aerosol, sulfur dioxide, nitrogen oxides, ozone, and carbon monoxide cause numerous dire consequences on human health and culminate in premature deaths [2]. Among these pollutants, nitrogen oxides (NOx) and carbon monoxide have garnered great attention over the last decades, triggering serious concern over the release of these gases into the atmosphere. Various factors are effective in the generation of

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the nitrogen oxides and carbon monoxide and they are introduced as air pollutant indicators over the recent years. Among all, mobile sources such as diesel cars and vehicles as well as motorcycles have the highest contribution in the nitrogen oxides and carbon monoxide generation. According to the conducted studies, about 70% to 80% of air pollution is caused by cars and other vehicles, and the rest is caused by industry and other sources [3]. Therefore, it is crucial to control the air pollutants in order to provide a clean and pleasant environment.

Exhausted gases resulting from combustion of gasoline and diesel fuels abound with nitrogen oxides that are very toxic. The high temperature inside the automobile cylinder is the most important factor in NOx generation. The bond between the nitrogen molecules is broken due to the high temperature of the combustion chamber in which the constituted molecules tend to react with the existing oxygen. Nitrogen dioxides (NOx) can cause serious respiratory and eye inflammation problems in humans. It can also prompt olfactory malady, fatigue, throat sore, nervous disorders, and acute bronchitis. Furthermore, NOx can be precursor to other pollutants like ozone. The amount of NOx produced in old and exhausted cars and carburetor-types motorcycles is significantly high. With the rise of the ambient temperature and sun radiation, this produced NOx in the air is converted into ozone. As NOx released to the ambient, the secondary chemical reaction occurs in the air in which the existing NOx is being converted into ozone at the lower atmosphere. It should be noted that ozone is very pernicious and is invisible to the naked eye and can jeopardize the human life by prompting cancer and lung diseases [4]. On the other hand, transportation is one of the main causes of greenhouse gases emissions. Greenhouse gases (carbon dioxide, methane, etc.) are produced directly by burning fossil fuels or indirectly by generating other types of energy using fossil fuels. Automobiles are the primary source of carbon dioxide emissions in urban areas which produce about half of the carbon dioxide emitted into the atmosphere. The rise in the concentration of greenhouse gases is known as one of the main factors in the climate change of the globe. Many environmentalists believe that the climate change directly and indirectly affects the economy of countries by reducing agricultural and industrial productions or increasing the mortality rate.

Normally, catalysts are used to purify gases and pollutants of the exhaust gases expelling from the gasoline and diesel engines. The most important pollutants are carbon monoxide (CO), nitrogen oxides (NOx), and unburned hydrocarbons. Installing catalysts on the exhaust pipe of automobiles to control the emission of pollutants dramatically reduces the amount of pollution. One of the main features of catalysts is their high potentials in enhancement of the heat absorption process, thereby reducing the engine temperature. If a vehicle does not have a right catalyst, NOx is produced. The catalyst makes 90% of the toxic gases ineffective by converting the unburned hydrocarbons exiting from the engine into water and carbon dioxide. In addition, a catalyst can be significantly effective in reducing the air pollution as they convert nitrous oxide to nitrogen gas. Another way to decrease fuel consumption and pollution emission in the combustion process is to provide an ideal condition for homogeneous combustion. This condition can be provided by using porous media in the combustion chamber. Flow transport in porous media can be seen in many industrial processes such as filtration and catalysts. Providing a homogeneous mixture of fuel and air by inserting porous media in internal combustion engines (ICEs) has many advantages, including but not limited to significant reduction of pollutants as well as specific fuel consumption, while improving efficiency [3]. The following are some examples of research conducted in the field of decreasing pollutants in the combustion chamber.

A research assessing the durability of the SCR-DPF systems applicable for trucks with heavy duty was conducted by Conway et al. [5]. Their results indicated that the cost of fuel can be improved by reducing NOx emission of the system. Wardana et al. [6] employed the SCR model and modeled the uniformity of ammonia in the catalyst inlet section and observed a reduction of NOx in the uniform mixture. The effects of using a spray on exhaust gases of diesel engines in the SCR after-treatment systems were numerically and experimentally investigated by Varna et al. [7]. According to their results, the vortex generation and the interaction between the wall and spray were not vivid at higher cross-flow velocities, resulting in a distraction in the concentration uniformity at the down-stream areas. A simulation related to a multi-stream injector aimed for urea-dosing in an SCR exhaust gas system was carried out by Varna and Boulouchos [8]. They discussed the influence of vortex generation behind the spray core and other pivotal phenomena and their importance at various conditions. They reported a decrement in strength of the spray core and vortices. Auvray et al. [9] proposed a precise kinetic model in order to simulate the SCR reaction and component reactions throughout the monolith catalyst system spatiotemporally and introduced inertia-catalyst spatial data as an asset. Baleta et al. [10] simulated the SNCR process in a 3-D industrial reactor to assess the SNCR efficiency and temperature as well as NOx reduction under the effects of several parameters. Wardana et al. [11] carried out numerical and experimental studies to investigate the desired airflow and temperature and calculate NOx reduction efficiency under the effects of urea injection timing. Improvement in NOx conversion due to the influence of urea injection timing and wall temperatures was the main result of their work. Using SCR catalyst with a diesel particulate filter (DPF), Marchitti et al. [12] experimented the mutual interactions of NH3-SCR and particulate matter oxidation. The effects of NO, NO2, and NH3/NOx co-existence on soot combustion were scrutinized. They figured out that compared to O2, NO2 oxidizes soot to COx at lower temperatures. Smith et al. [13] evaluated both pre- and post-impingement sprays by utilizing the laser diffraction method. According to the results, the accuracy of the simulation can be remarkably risen for various exhaust pipe shapes. Sarafraz et al. [14, 15] tested the chemical performance of a novel catalyst inserted in a micro-reactor to produce hydrogen. Their results indicated diffusion-controlled as the mechanism of hydrogen and synthetic gas production. Regarding this, it was found that increasing the flow rate of the reactants causes a reduction in the residence time, leading to decrement of methanol conversion extent.

The idea of using porous media in ICEs was first proposed by Durst and Weclas [16, 17]. They investigated the performance of porous media on a single-cylinder diesel engine with direct injection mechanism. Their results showed that using porous media improves the engine efficiency, while reducing the pollutants emissions. Chein et al. [18] utilized porous media in a directly injected diesel engine to achieve a homogeneous combustion with nearly zero emissions. The results reported by these authors indicated that a significant reduction in pollutants emissions in all operating conditions of the engine can be achieved. They also reported an increment in the output power due to the rapid mix of air and combustion in the porous media. The results also indicated that the amount of NOx decreases dramatically, while the amount of soot and unburned hydrocarbons rise. The effects of using porous media with high porosity on the performance of a single-cylinder diesel engine and the amount of pollutants emissions were studied by Kannan and Tamilporal [19-21] and compared their results with those reported for a conventional engine. The results showed a subtle decrease in the engine efficiency with the increase of load, while NOx generation is decreasing since inserting porous media increases controllability of the combustion temperature. However, when the load was low, the amounts of soot and NOx in the engine designed with porous media are higher than those calculated for the conventional one. Saravanan et al. [22] carried out an experimental comparison between the results of the conventional engine and the engine with inserted porous media in terms of performance and the pollutants emissions. In this comparison, the amount of NOx was measured for loads of 100, 80, 60, 40, 20, and 0%. The amount of NOx in the engine with inserted porous media is lower than that emitted by the conventional engine, in which its value is constant for all investigated loads. Moreover, the exhaust gas temperature, the specific fuel consumption, and the brake efficiency of the engine with inserted porous media were around 16.6%, 9.8%, and 8.7% lower than those values of the conventional engine, respectively. Zhou et al. [23] investigated the effective heat transfer between the gas and the porous media with periodic motion in the engine cylinder and reported significant improvement in the combustion efficiency and a reduction in the pollutants emissions. Kaviany and Park [24] investigated the effects of porous media on the performance of the diesel engines. Their results substantiated the fact that the super-adiabatic flame temperature (SAFT) and contact between the fuel droplets and porous media expedite the fuel evaporation. Zhigou and Mahozhao [25] evaluated the effects of different parameters such as initial temperature, porous media structure, and fuel injection time on the combustion phenomenon. They found that the initial temperature of porous media is a key factor at the onset of combustion in porous media. Ge et al. [26] thermodynamically analyzed the performance of a recovery cycle in an engine inserted with porous media. They proposed a relation between the output power, compression ratio, and efficiency. They also proposed an optimal relation between the output power and cycle efficiency with heat transfer and friction drop. Dhale et al [27] studied the efficiency, soot formation, and fuel consumption in plain and porous combustion chambers and showed an augmentation in the engine efficiency by using porous media. They also found out that the amounts of NOx, carbon monoxide, and unburned hydrocarbons were remarkably reduced, and the amount of soot can be negligible.

Of the important issues that should be considered in the design of internal combustion engines are reducing fuel consumption, improving efficiency, and reducing environmental pollution during the combustion process. Therefore, in this work, the effects of temperature, mass flow rate of the injected fuel, pore diameter, porosity and ambient pressure on the amount of pollutants in the combustion chamber is investigated for the first time. This study aims at reducing the temperature of the exhaust gases as well as the destructive effects of nitrogen oxides as well as other pollutants by injecting a compound of urea-water into the inlet gases entering the porous chamber (catalyst). The numerical study of the exhaust pipe and catalyst inserted with porous media can lead to significant reduction in the pollutants emissions, and hence can be helpful for the auto designers in predicting and reducing the amount of pernicious gases like NOx in the auto industry. It should be noted that the idea of reducing the vehicle pollution by using porous media and combined urea-water injection into entering gases of the catalyst has not been addressed before.

## 2 Problem statement and boundary conditions

As illustrated in Fig. (1), urea solution is injected into the exhaust stream prior to the catalyst which is considered to be porous. This compound enters into the catalyst with nitrogen and other elements. The exhaust heat converts the urea solution to $\mathrm{NH_3}$.The reaction of $\mathrm{NH_3}$with $\mathrm{NO}$ and $\mathrm{NO_2}$ inside the catalyst produces nitrogen gas ($\mathrm{N_2}$) and water vapor ($\mathrm{H_2O}$) in which both are known as environmentally-friendly element. It should be noted that the reason for using urea is to reduce $\mathrm{NO}$ pollutants in the combustion gases. Injection of water vapor into the combustion chamber decreases CO emission which is due to the decrease in the temperature and decomposition reaction of $CO_2$. Moreover, the water vapor injection also increases the amount of unburnt fuel which itself decreases the CO production.

Inlet and outlet boundary conditions are considered as the mass flow inlet and pressure outlet, respectively. Other boundary conditions are assumed as walls.

$$\mathrm{N}H_2\mathrm{CO}\ \mathrm{N}H_2+H_2O \rightarrow \mathrm{N}H_4^{+}+ H_2\mathrm{NCOO}^{-}= \mathrm{N}H_3+H_2\mathrm{NCOO}^{-} \tag{1}$$

$$\mathrm{NO}+\mathrm{N}H_3+\mathrm{N}O_2 \rightarrow N_2+H_2\mathrm{O} \tag{2}$$

## 3 Governing equations

The flow inside the ICE is assumed three-dimensional, incompressible, steady state, and turbulent. The k-ε-RNG turbulent model was used to model the turbulence for resistance against torsional and rotational effects. Also, the discrete phase model (DPM) based on the Lagrangian approach was used to simulate the flow field. In this model, the continuous phase was first calculated by the time-averaged Navier-Stokes equations. Then, particle tracking calculations were carried out. Afterward, the continuous phase equations were corrected by incorporating mass, momentum, and energy sources. These equations are solved again, and the process continues until the particles reach the outlet.
The conservation equations of mass, momentum and energy in the time-averaged form are written respectively as follows:

$$\frac{\partial}{\partial x_j}(u_j) = 0 \tag{3}$$

$$\frac{\partial}{\partial x_j}(u_i u_j) = -\frac{1}{\rho}\frac{\partial}{\partial x_j}[p + \frac{2}{3}\rho k \delta_{ij}] + \frac{\mu_{eff}}{\rho}[2\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\left(\frac{\partial u_k}{\partial x_k}\right)] \tag{4}$$

$$\frac{\partial}{\partial x_j}(u_j e_s) = \frac{1}{\rho}\frac{\partial}{\partial x_j}[\gamma \frac{\mu_{eff}}{\sigma_{eff}}\frac{\partial e_s}{\partial x_j}] - \frac{1}{\rho}\frac{\partial}{\partial x_j}(p u_j) \tag{5}$$

The equation of homogeneous porous media is stated as follows:

$$S_i = -(\frac{\mu}{\alpha}V_i + C_2\frac{1}{2}\rho|V|V_i) \tag{6}$$

Where $S_i$ is the source term, $\alpha$ is the permeability and $C_2$ is the inertial resistance coefficient. The permeability and inertial resistance coefficient in each component direction identified as:

$$\alpha = \frac{D_p^2}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2} \quad , \quad c_2 = \frac{3.5}{D_p}\frac{1-\varepsilon}{\varepsilon^3} \tag{7}$$

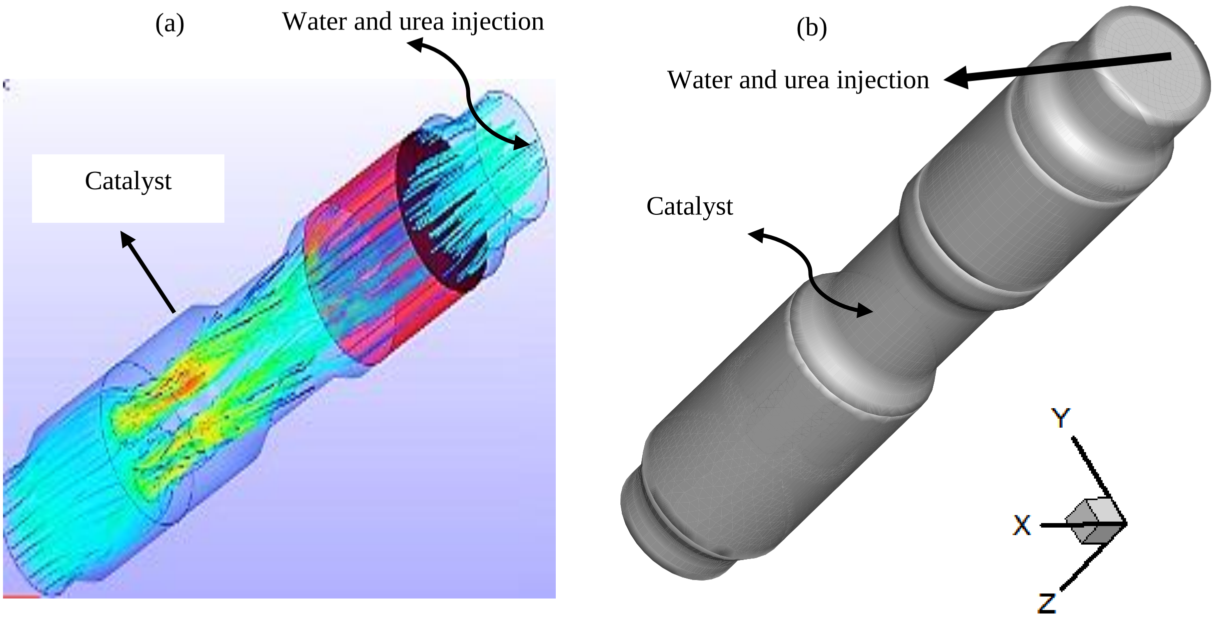



**Figure 1** (a) Schematic of porous catalyst and (b) 3-D illustration of porous catalyst.

The equations of the k-ε-RNG turbulence model are stated as follows:

$$\frac{\partial}{\partial x_j}\left(u_j K\right) = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k}\frac{\partial K}{\partial x_j}\right] + \frac{\mu_t}{\rho}\left(\frac{\partial u_i}{\partial x_j}\right)^2 - \varepsilon \tag{8}$$

$$\frac{\partial}{\partial x_j}\left(u_j \varepsilon\right) = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + c_1\frac{\varepsilon}{K}\left[\mu_t\left(\frac{\partial u_j}{\partial x_j}\right)\right]^2 + c_2\frac{\varepsilon^2}{K} + c_3\varepsilon\frac{\partial u_j}{\partial x_j} \tag{9}$$

Also, the Eulerian-Lagrangian method for estimating the particles behavior is expressed as below:

$$m_p\frac{d\overrightarrow{u_p}}{dt} = m_p\frac{\vec{u}-\overrightarrow{u_p}}{\tau_r} + m_p\frac{\vec{g}(\rho_p-\rho)}{\rho_p} + \vec{F} \tag{10}$$

$$\tau_r = \frac{\rho_p}{18\mu}d_p^2\frac{24}{c_d Re} \tag{11}$$

$$Re = \frac{\rho d_p}{\mu}\left|\overrightarrow{u_p} - \vec{u}\right| \tag{12}$$

Where, $m_p$, $\overrightarrow{u_p}$, and $\rho_p$ refer to the mass, velocity and density of particles, respectively. Also, $\vec{u}$ is the fluid phase velocity, $\rho$ is the fluid density, $Re$ is the relative Reynolds number, $m_p\frac{\vec{u}-\overrightarrow{u_p}}{\tau_r}$ is drag force, $\vec{F}$ denotes other possible additional forces, $\tau_r$ is relaxation time of particles, μ is molecular viscosity of particles, and $d_p$ is diameter of particles.

## 4. Mechanism of mass transfer on the surface of the catalyst

In studying the processes of heat transfer, a pellet of catalyst can be considered to be homogeneous because a temperature field is averaged not only by its free volume filled with the reaction mixture, but also its solid phase, which has a far higher heat conductivity. Also, owing to the extremely developed internal surface intense heat exchange occurs between the two, phases, resulting in homogenization of the system. It is therefore justifiable to use the Fourier law.

When a reaction occurs inside a catalytic particle, the reagents are consumed for giving products and a certain amount of heat is consumed or released according to the thermal characteristic of the reaction (exothermic or endothermic). The concentration of the reagents decreases from the external geometric surface of the particles toward the center. The concentration of the products, on the contrary, increases. The temperature changes as a consequence of the heat consumed or released by the reaction, increasing or decreasing from the external surface to the center of the catalytic particle. In other words, the reaction is responsible of the concentration and temperature gradients originating inside the particle that act as driving forces for both the mass and heat transfer inside the catalyst particle. The faster the reaction, the steeper the gradients. In the case of high reaction rate, this effect is propagated toward the external part of the catalyst particle, generating other gradients of concentration and temperature between the catalyst surface and the bulk fluid. When the fluid flow regime is turbulent, as normally occurs in industrial reactors, the external gradients are confined to very thin layer, named the boundary layer, that surrounds the solid surface. The boundary layer is quiescent, and consequently mass and heat transfer occur through it, with a relatively slow process characterized by the molecular diffusion mechanism. The effects of reaction and diffusion rates are concentration and temperature profiles, respectively. External diffusion and chemical reaction are consecutive steps, and their contributions to the overall reaction rates can be considered separately. A similar approach cannot be adopted for the internal diffusion as it occurs simultaneously with the chemical reaction. To describe the influence of internal diffusion on reaction rate requires solving the mass and heat balance equations related to any single particle for evaluating the concentration and temperature profiles.

## 5 Numerical method

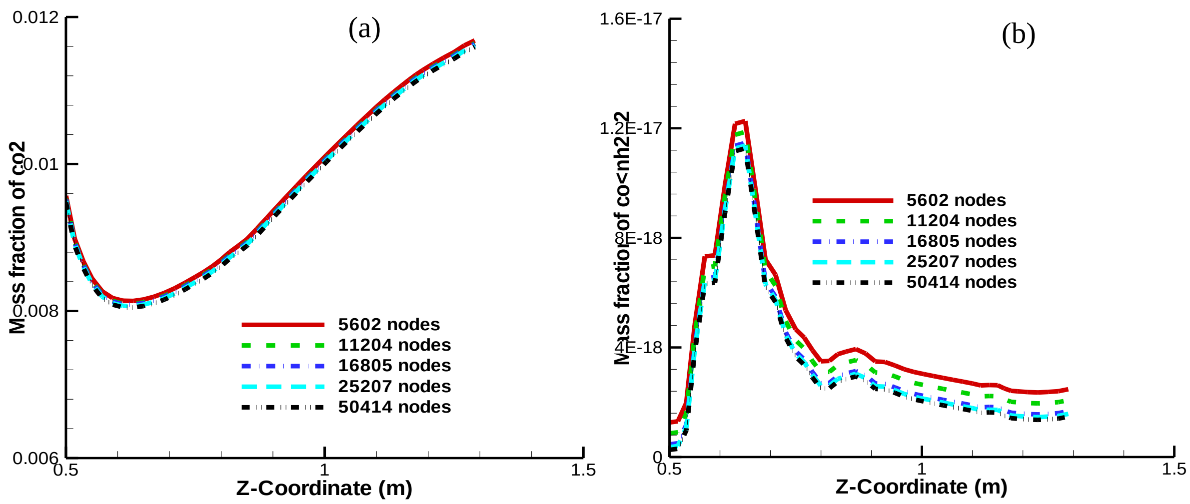
The finite volume method (FVM) is applied for discretization of the governing equations, in which the pressure-based algorithm was used due to the incompressibility of the flow. The flow field is simulated under steady state and 3-D conditions by employing a separate solver with absolute velocity formulation to solve the equations. Also, SIMPLE algorithm was used for coupling pressure and momentum equations. Second-order upwind method was used for discretization of the pressure and momentum terms, while the first order upwind method was used for discretization of the turbulent kinetic energy and dissipation rate. For a precise simulation, the convergence residuals for all variables were considered less than 10E-6.

## 6 Grid independency

The effect of node number on the mass fraction of species is illustrated in Fig. 2. Fig. 2 reveals that for 25207 nodes, the calculation is independent of the nodes' number. Fig. 3 shows the sketch of the generated grid to study the flow inside the ICE.

## 7 Validation

To validate the accuracy of the employed numerical models for the current simulation, the results are compared with the experimental data obtained for porous catalyst in Ref. [28]. According to this comparison, the difference between the present work and the experimental work is low, which confirms the accuracy of the present calculation approach.



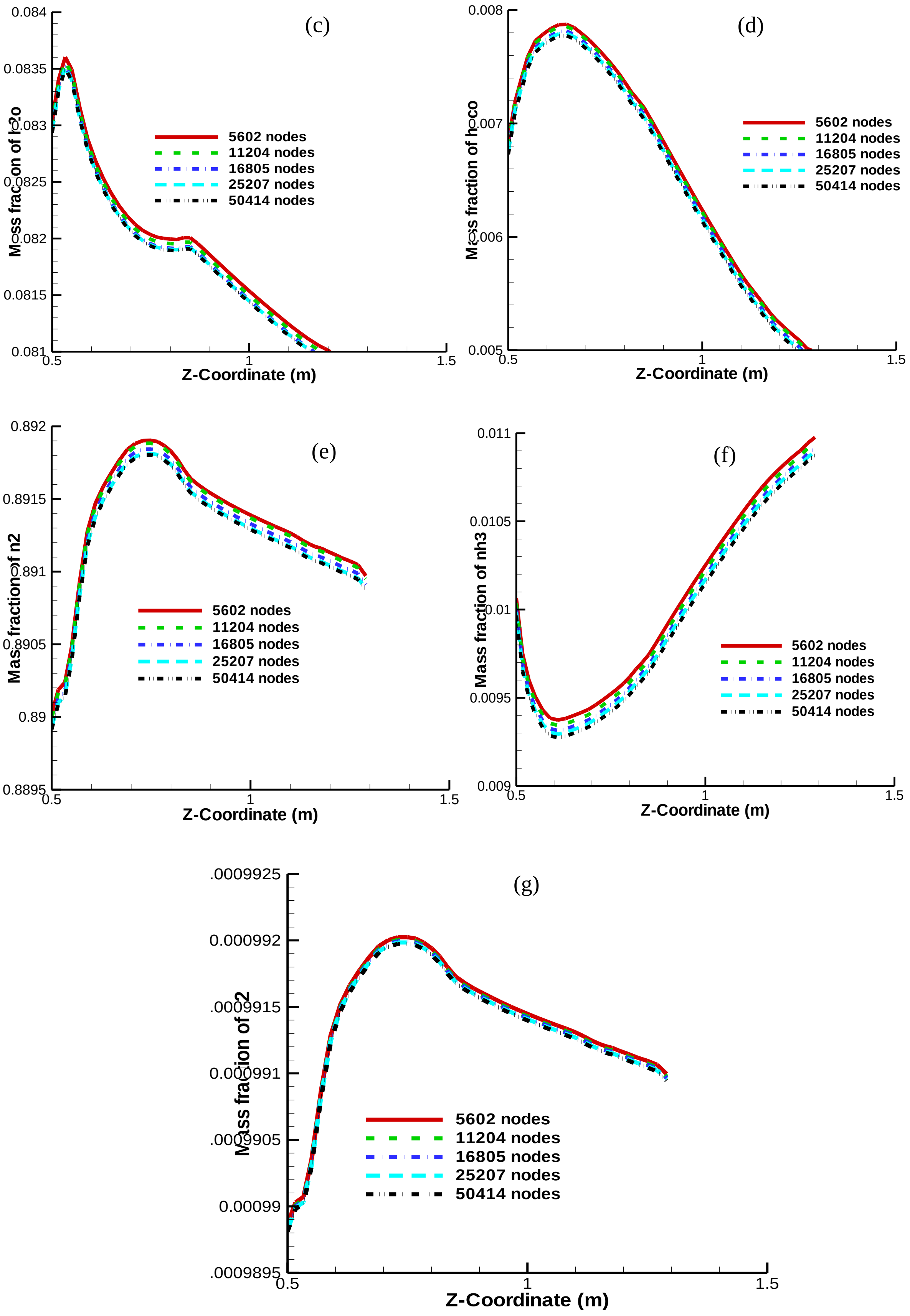



**Figure 2** The effect of node number on the mass fraction of (a) $CO_2$ (b) CO$(NH_2)_2$ (c) $H_2$O (d) HNCO (e) $N_2$ (f) $NH_3$(g) $O_2$ .

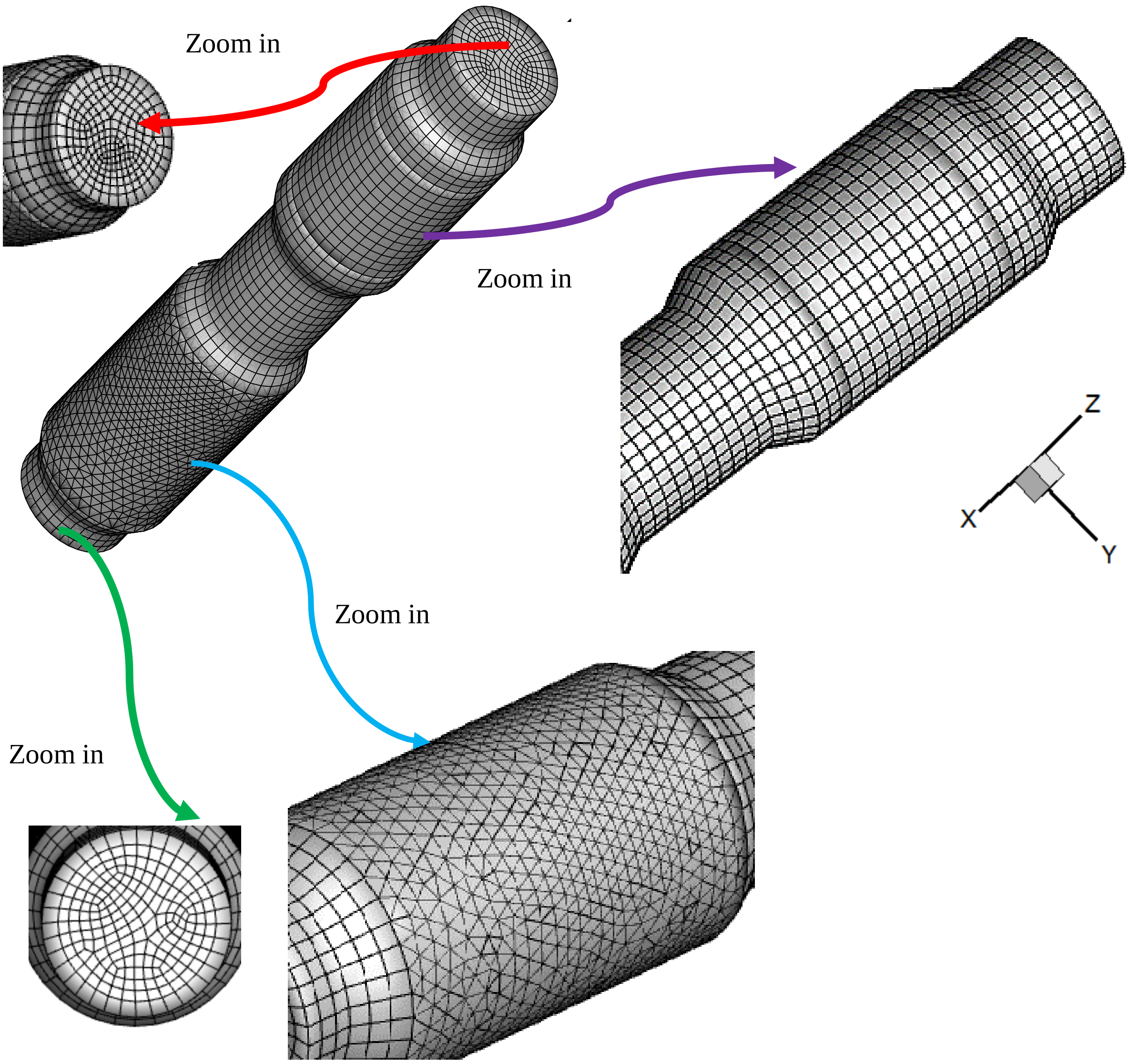



**Figure 3** Schematic of calculation grid to study the flow inside the ICE.

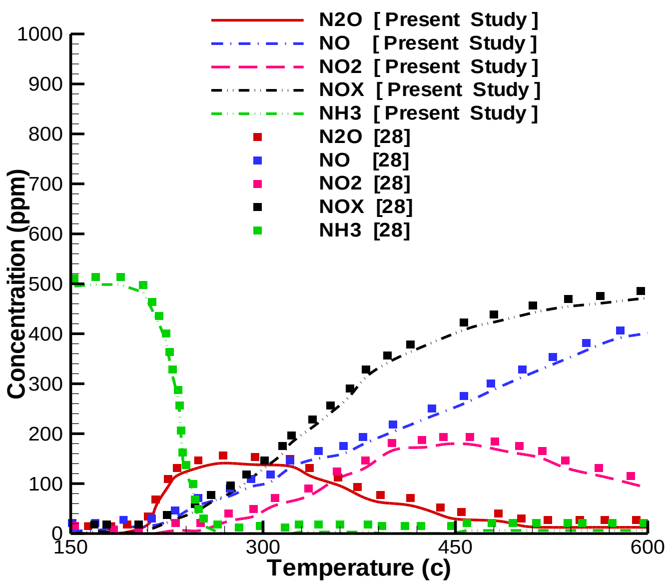


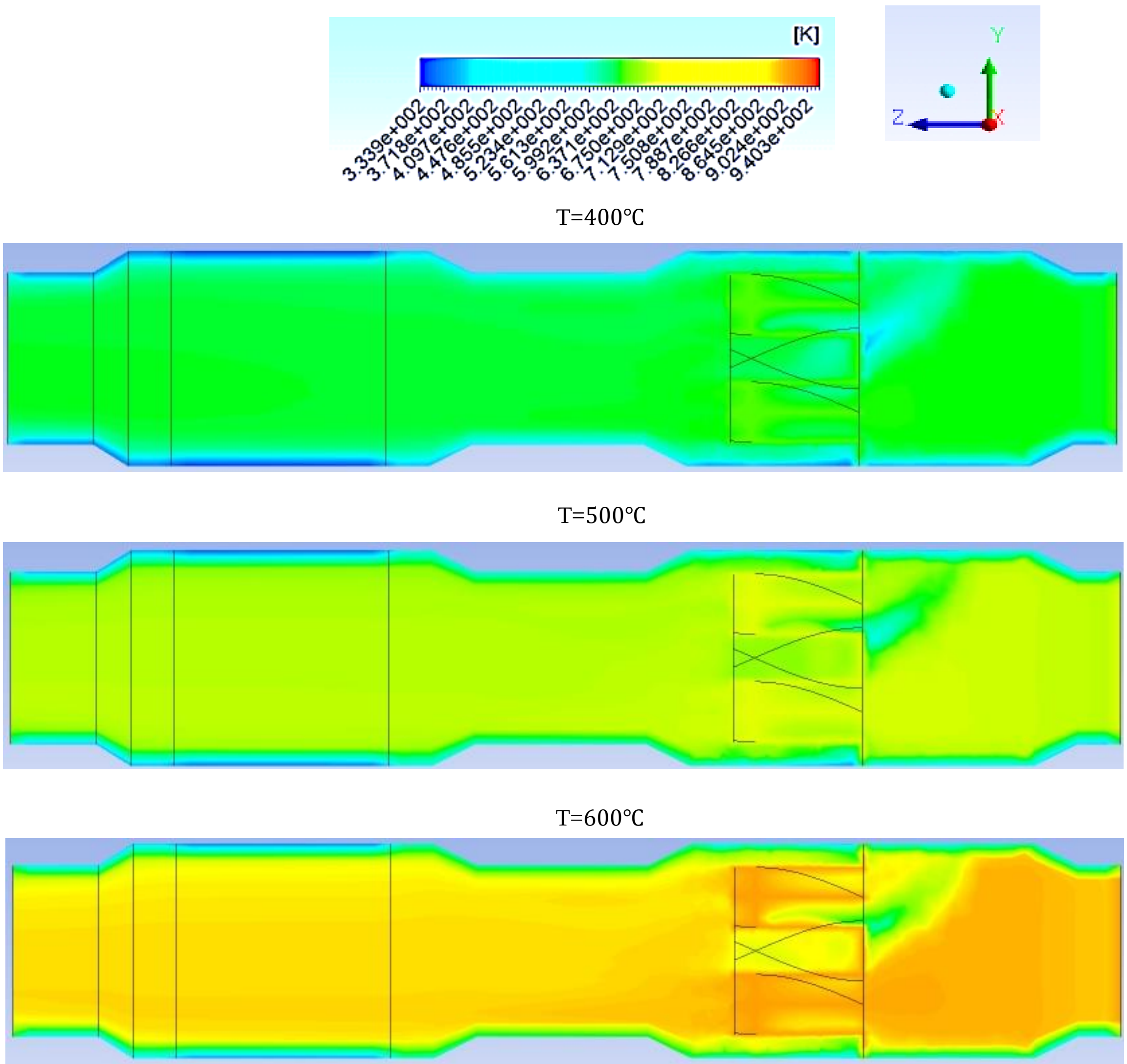

**Figure 4** Comparison of the concentration distribution of (a) No (b) $No_2$ (c) $N_2o$ (d) $No_x$ (e) $NH_3$ in current work and experimental study in the literature [28].

## 8 Results and discussions

In this section, the results of simulation of the combustion process and the effects of the temperature, mass flow rate of the injected fuel, pore diameter, porosity, and ambient pressure on the amount of pollutants are presented and discussed.

### *8.1 Increasing temperature*

Figs. 5 to 7 represent the varying trend of temperature, the mass fraction of nitrogen gas, and carbon dioxide in the combustion chamber. As can be seen, the temperature distribution in combustion flames is more uniform with pre-heating the air. Hence, the combustion rate increases, thereby enhancing the combustion efficiency. It also increases the temperature of combustion products and production of thermal $NO_X$. Due to high combustion temperature, the presence of small amount of $N_2$ can produce considerable amounts of $NO_X$. Therefore, in order to decrease the destructive effects of nitrogen oxides as well as other pollutants, we have to decrease the temperature of the exhaust gases. In addition, the mass fraction of carbon monoxide is doubled with increasing the temperature which is mainly due to the high temperature and the breakdown of carbon dioxide molecules that are converted to the carbon monoxide.



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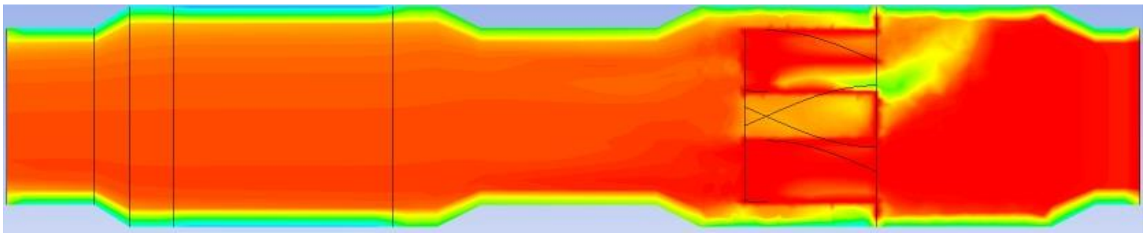
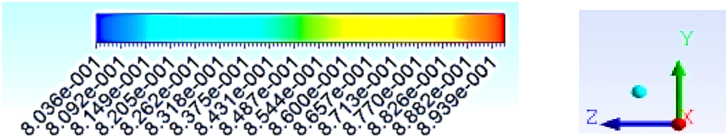


**Figure 5** The effects of pre-heating the air on the temperature distribution in the combustion chamber.

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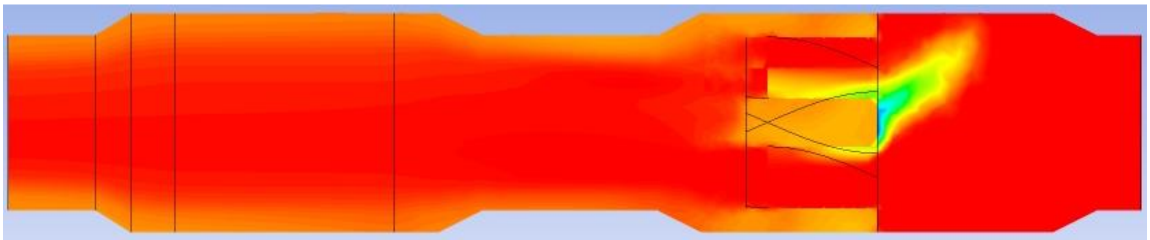

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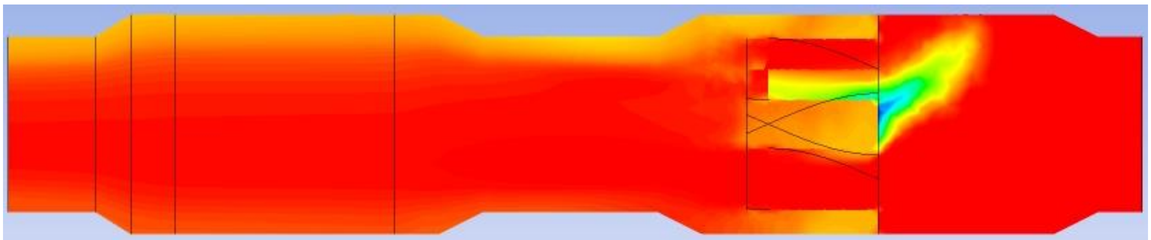

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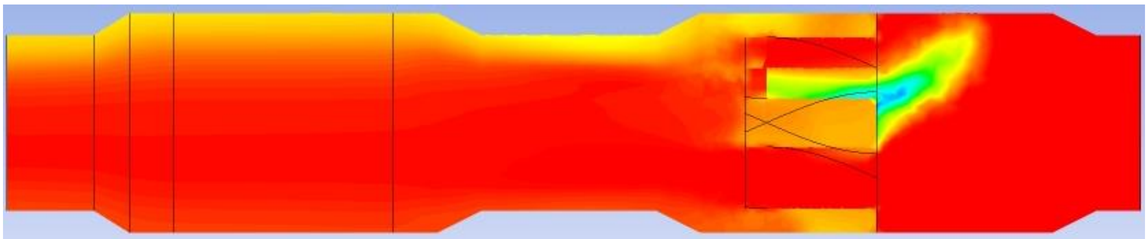

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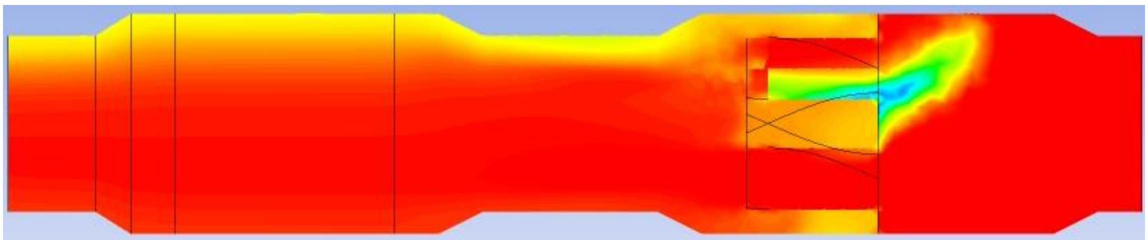


**Figure 6** The effects of pre-heating the air on the mass fraction of nitrogen gas in the combustion chamber

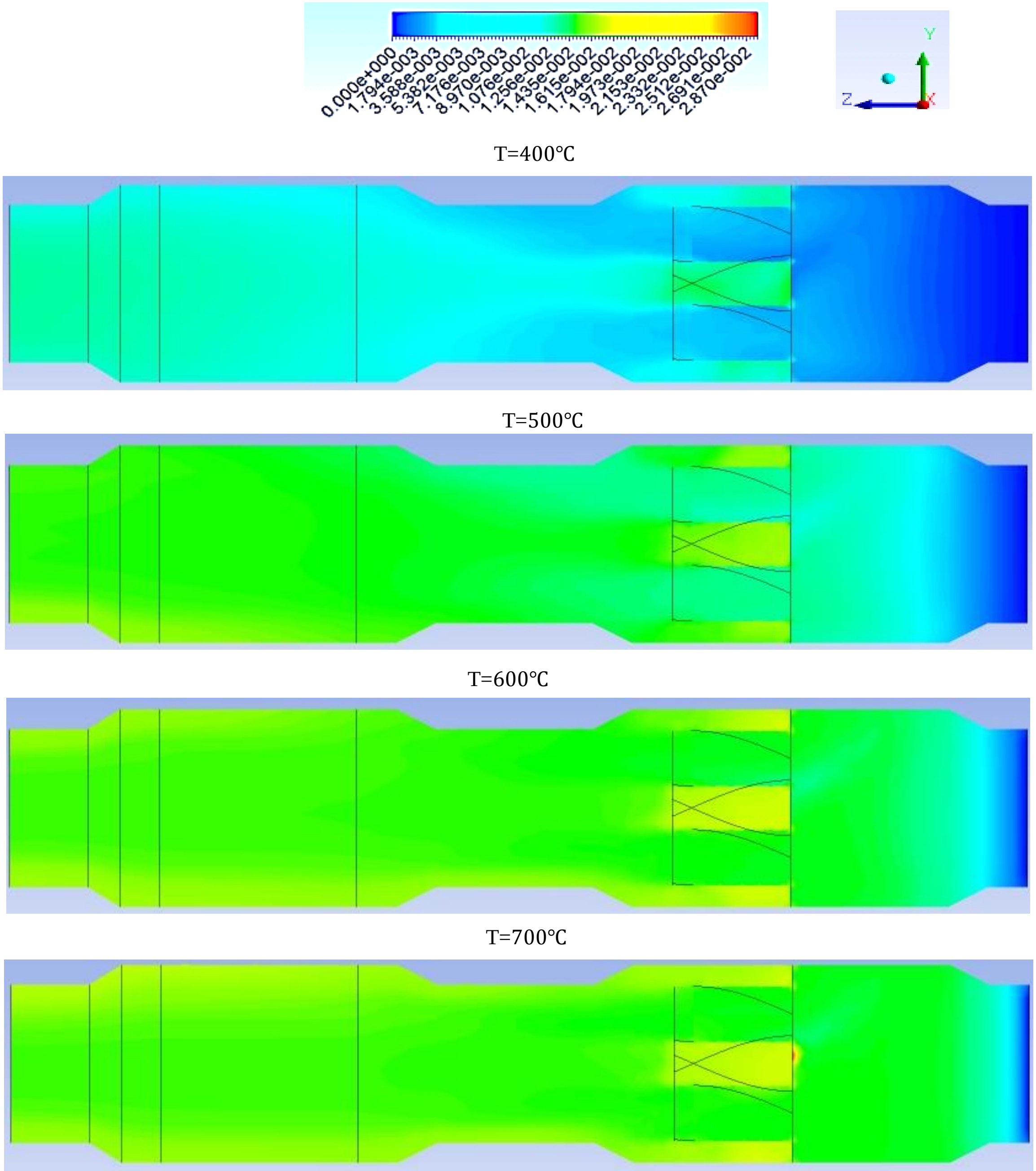
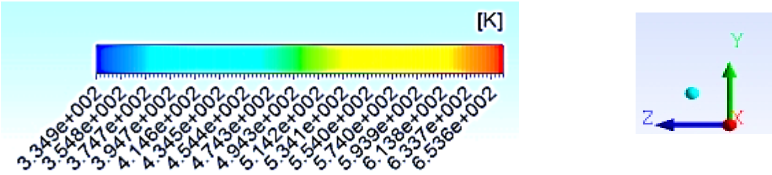


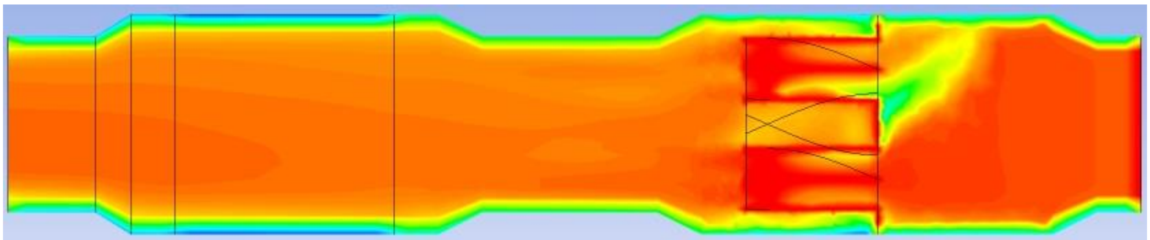

**Figure 7** The effects of pre-heating the air on the mass fraction of carbon dioxide in the combustion chamber.

### *8.2 Mass flow rate of the injected fuel*

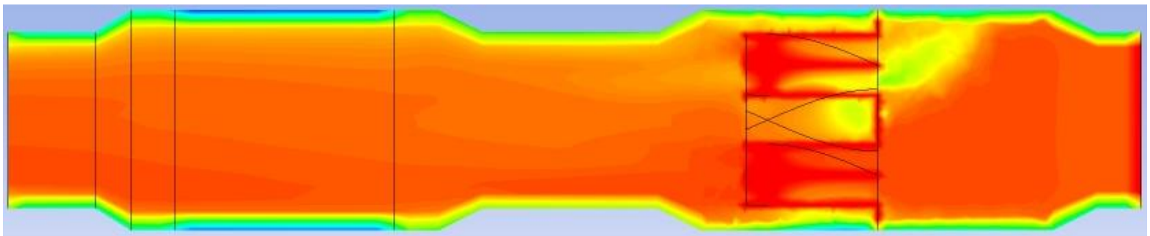
Figs. 8 to 10 represent the varying trend of temperature, nitrogen gas, and the mass fraction of carbon dioxide in the combustion chamber. As illustrated in Figs. 8 to 10, any rise in the mass flow rate of the injected fuel increases the maximum temperature of the liquid phase and the evaporation rate, thereby increasing the nitrogen monoxide (although this increment rate is small). Due to the high combustion temperature, the presence of small amount of $N_2$ can produce considerable amounts of $NO_X$. Also, the mass fraction of carbon dioxide decreases with the rise of the mass flow rate of the fuel injected into the cylinder, and hence less carbon monoxide is produced.




$\dot{m} = \dot{0}.0347754$kg/s



$\dot{m}$=0.0695508kg/s



$\dot{m}$=0.1391016kg/s

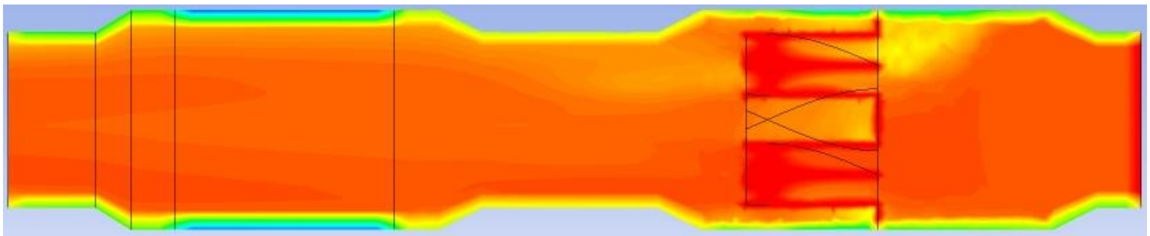
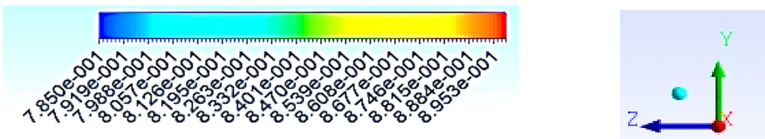
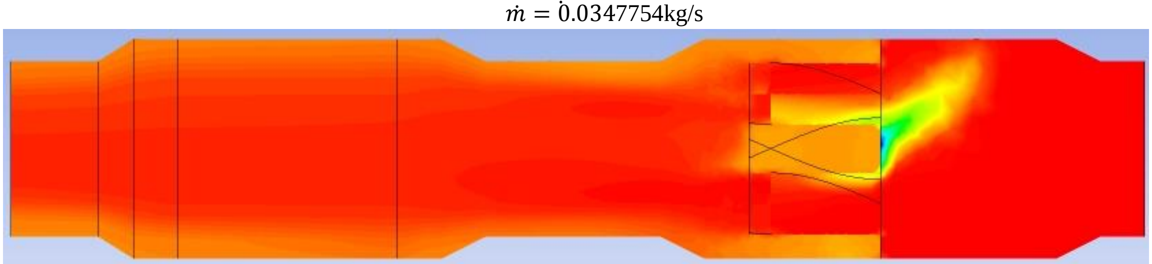


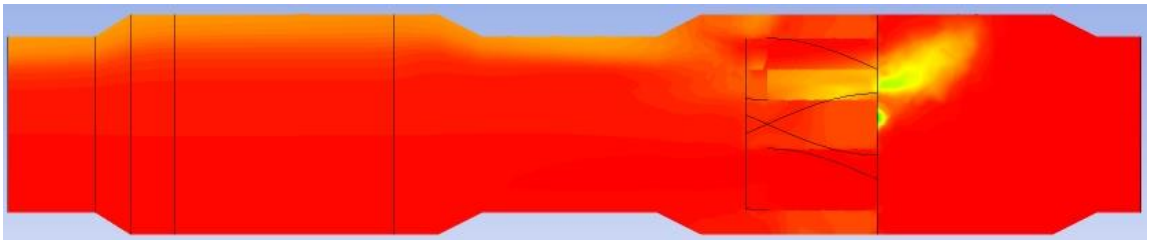
**Figure 8** The effects of the mass flow rate of the injected fuel on the temperature distribution in the combustion chamber.




$\dot{m} = \dot{0}.0347754$kg/s



$\dot{m}$=0.0695508kg/s



$\dot{m}$=0.1391016kg/s

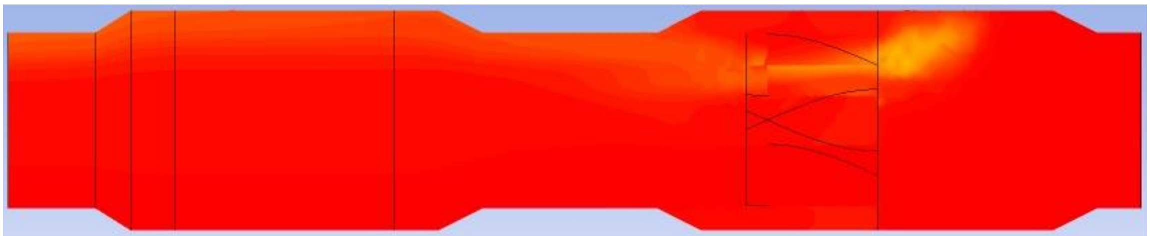
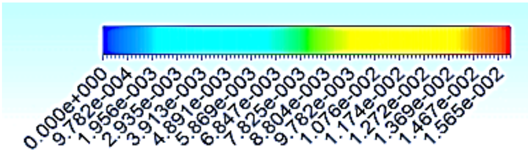
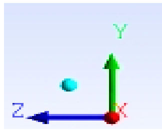
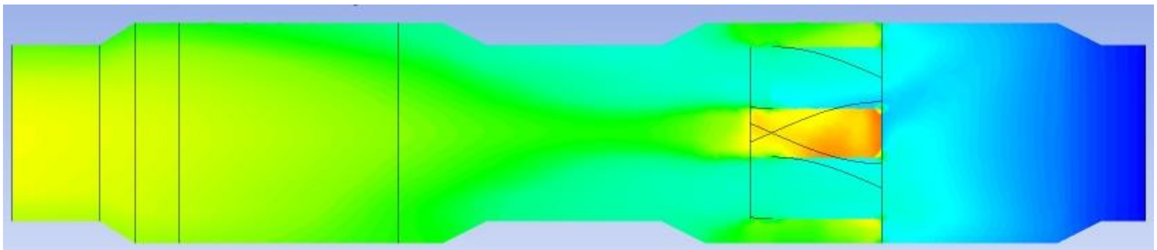


**Figure 9** The effects of the mass flow rate of the injected fuel on the mass fraction of nitrogen gas in the combustion chamber

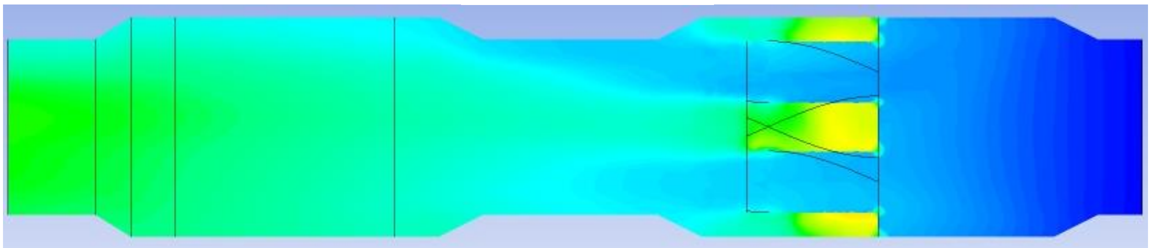



$\dot{m}$ = 0.0347754kg/s



$\dot{m}$=0.0695508 kg/s



$\dot{m}$=0.1391016kg/s

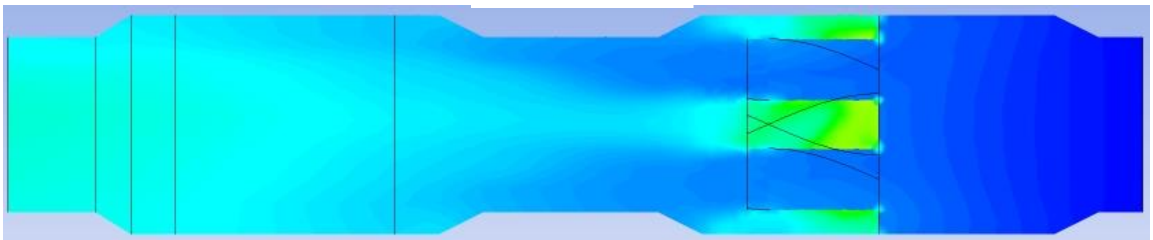


**Figure 10** The effects of the mass flow rate of the injected fuel on the mass fraction of carbon dioxide in the combustion chamber

Figs. (11) to (13) represent the varying trend of temperature, nitrogen gas, and the mass fraction of carbon dioxide in the combustion chamber. Any rise in the pore diameter results in the drop of the heat transfer coefficient, thereby increasing the average maximum temperature. Hence, the amount of nitrogen monoxide surges up with the increase of the pore diameter. Moreover, increasing the diameter of pores slightly reduces the amount of carbon monoxide since penetration of fuel droplets into the porous media occurs more easily with increasing the average diameter of pores. Therefore, the temperature gradient, which is the cause of carbon monoxide production, decreases. However, variation of pore diameter has no sensible effect on the combustion products.

In addition, the increase in pore diameter leads to increase in the combustion reaction rate which decreases the residence time of gas in combustion chamber and increases the temperature of outlet gas. Accordingly, and rise in the combustion rate and outlet gas temperature together increases the $NO_X$ emission.

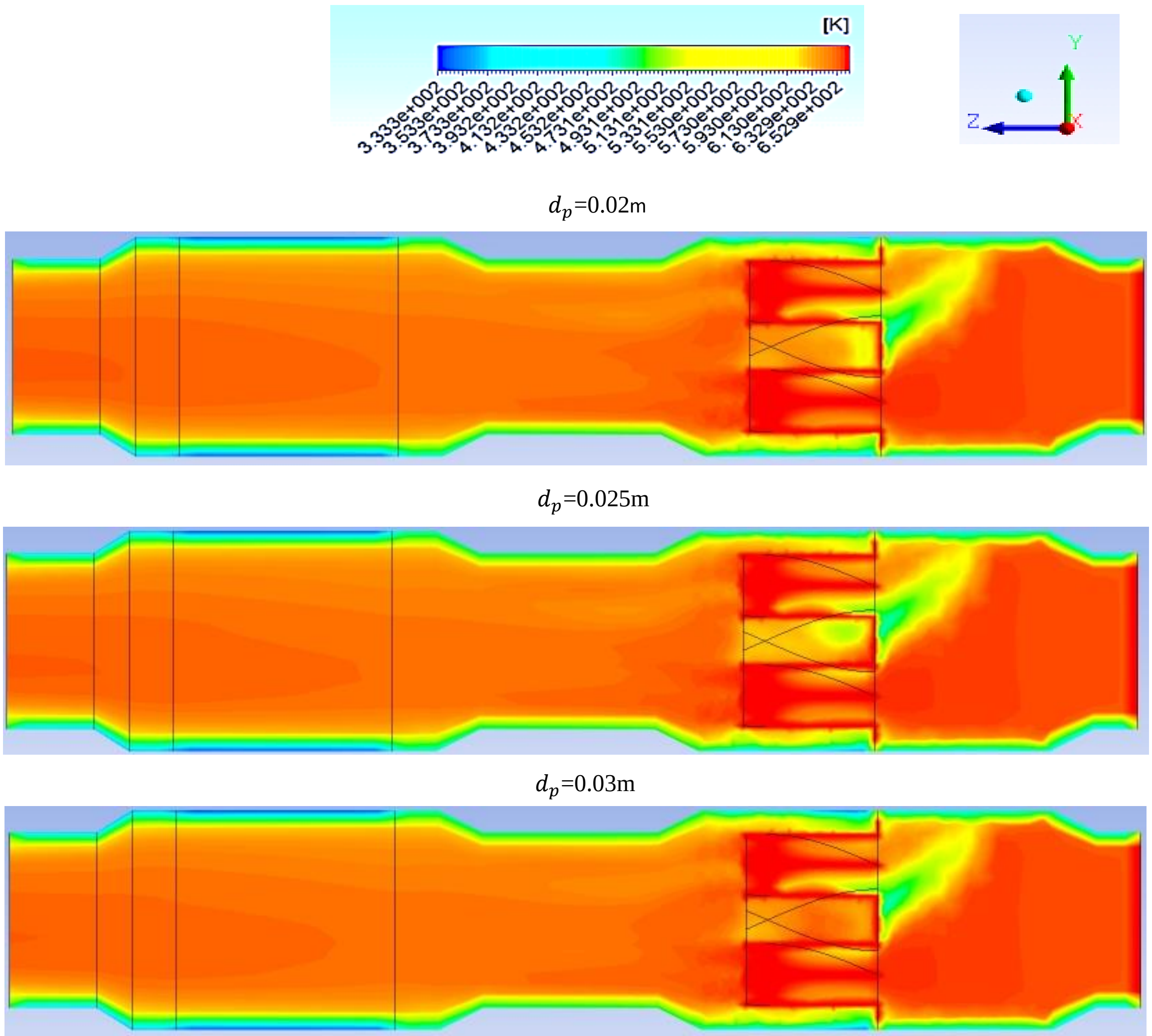
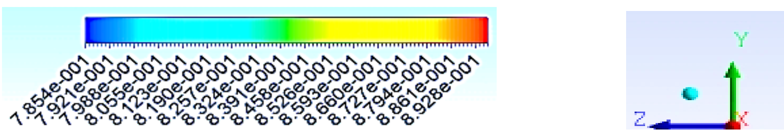
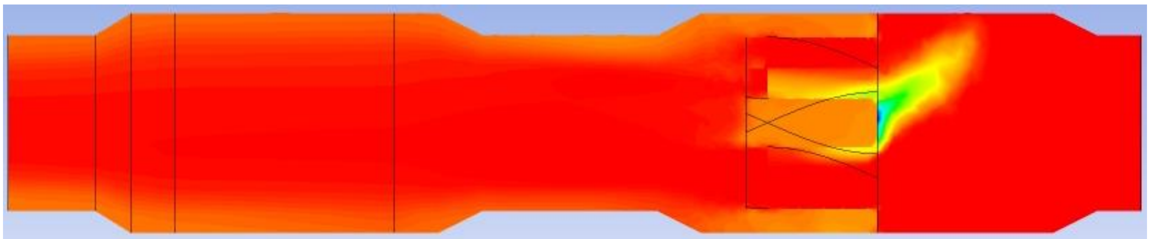


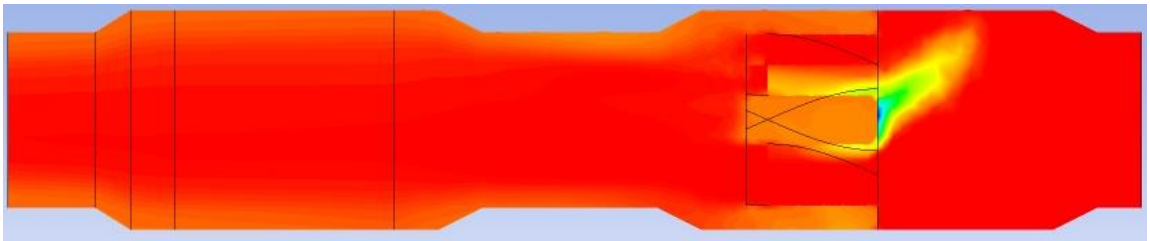

**Figure 11** The effects of the pore diameter on the temperature distribution in the combustion chamber.



$d_p$=0.02m



$d_p$=0.025m



$d_p$=0.03m

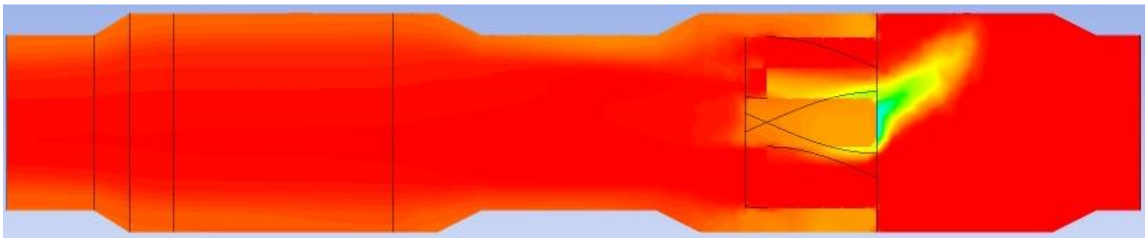
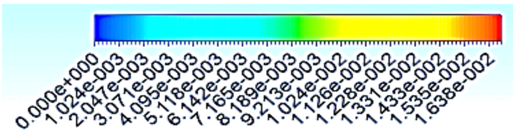
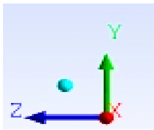
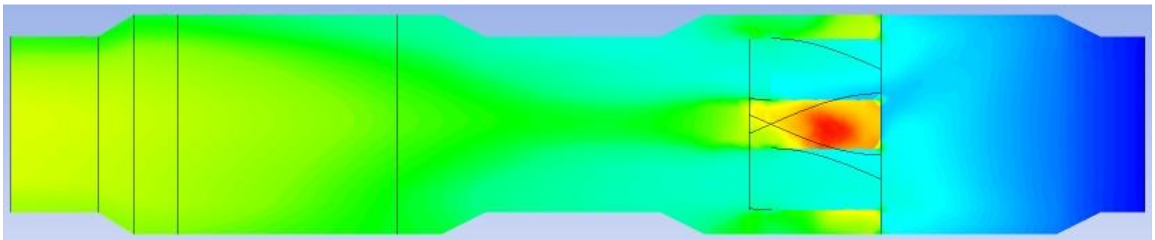


**Figure 12** The effects of the pore diameter on the mass fraction of nitrogen gas in the combustion chamber.

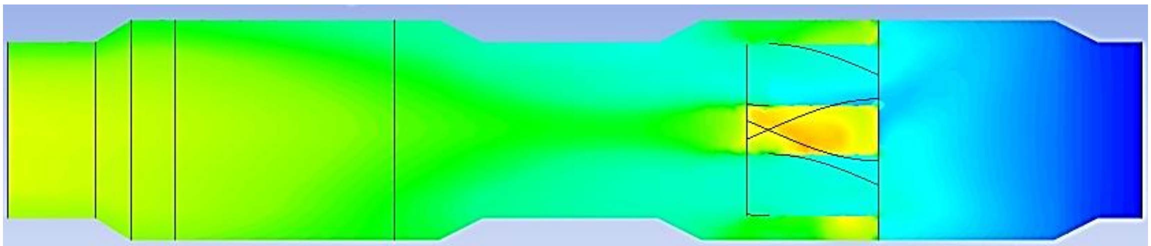



$d_p$=0.02m



$d_p$=0.025m



$d_p$=0.03m

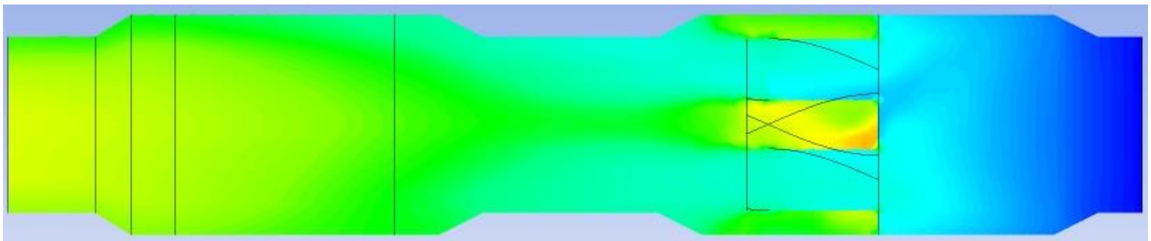
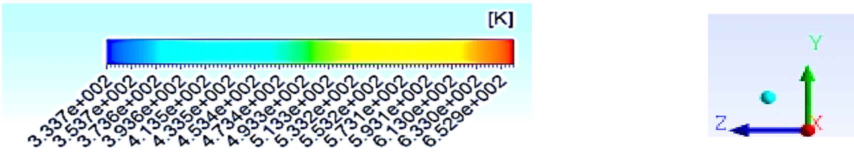


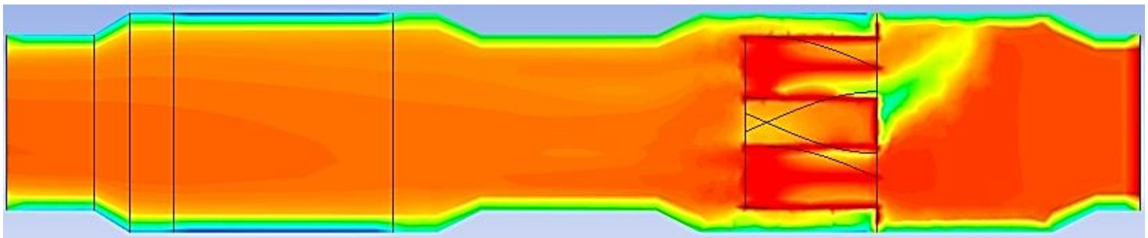
**Figure 13** The effects of the pore diameter on the mass fraction of carbon dioxide in the combustion chamber.

### *8.4 Effect of porosity*

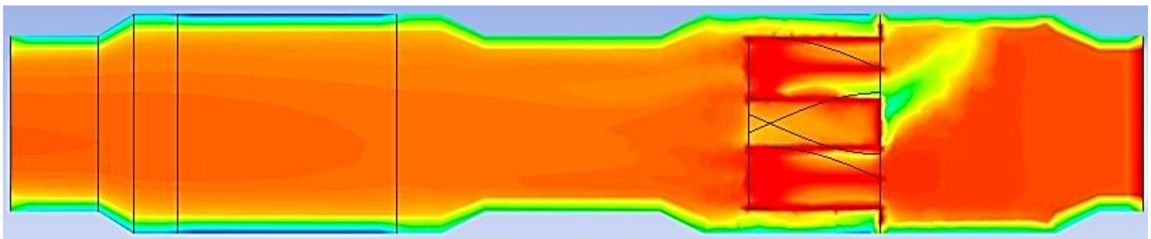
The results of simulation at different porosities (80%, 85%, and 90%) with homogeneous pore diameter of 0.020 m for distribution of temperature, $N_2$, and $CO_2$ are demonstrated in Figs. (14-16). Porous medium acts as a heat exchanger and effectively improves the heat transfer from combustion products to reactants. Increasing the heat transfer rate in porous medium leads to the decrease in the gas temperature and increase in the solid temperature. The decrease in the gas temperature reduces the $NO_X$ formation which requires high temperature. Furthermore, the production of unburnt hydrocarbon species like carbon monoxide is decreased due to better pre-heating in porous medium. Carbon monoxide emission is significantly reduced due to porosity of porous medium which gives enough opportunity for combustion of reactants. Generally, increasing the porosity makes heat distribution more uniform along the flame which increases the thermal efficiency and decreases fuel consumption.




$\varepsilon = 80\%$



$\varepsilon = 85\%$



$\boldsymbol{\varepsilon} = 90\%$

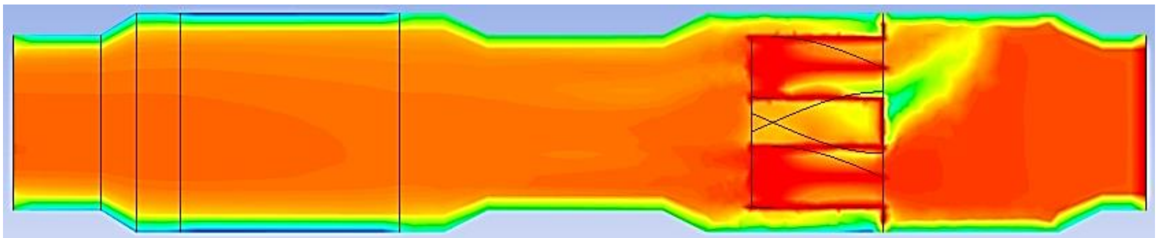
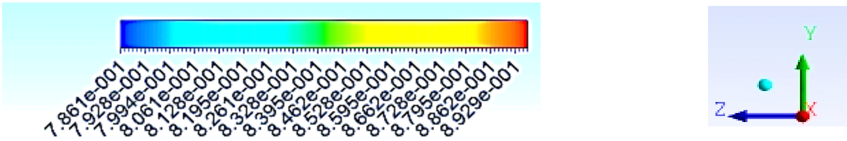
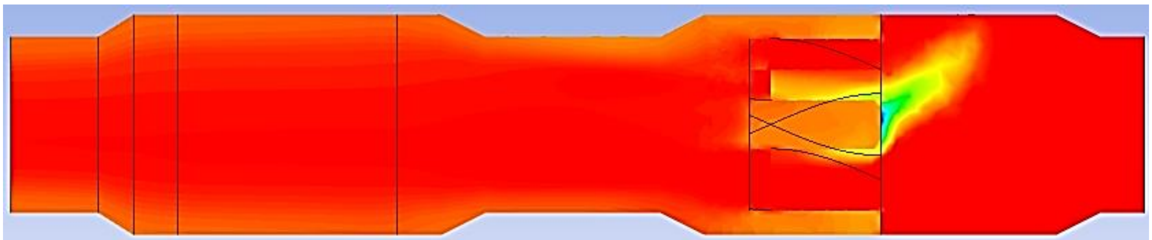


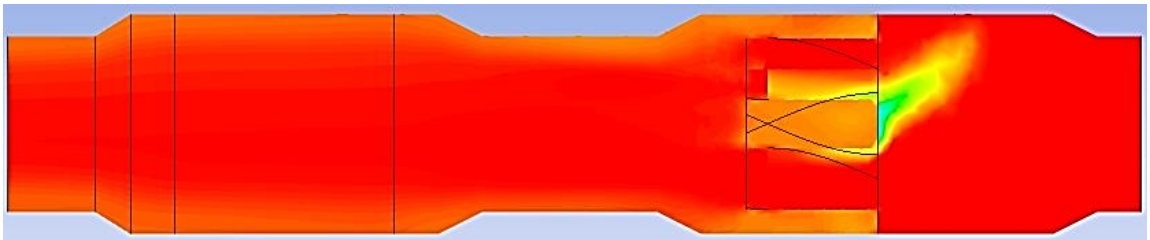
**Figure 14** The effects of the porosity on the temperature distribution in the combustion chamber.




$\boldsymbol{\varepsilon} = 80\%$



$\boldsymbol{\varepsilon} = 85\%$



$\boldsymbol{\varepsilon} = 90\%$

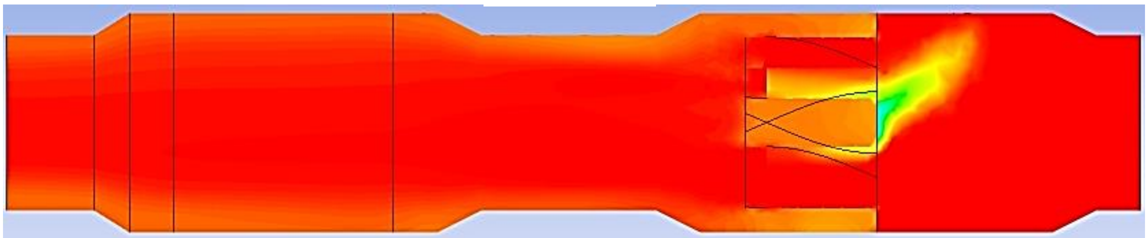
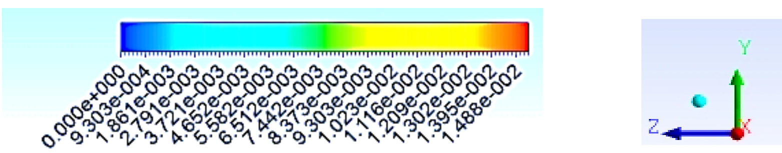


**Figure 15** The effects of the porosity on the mass fraction of nitrogen gas in the combustion chamber.



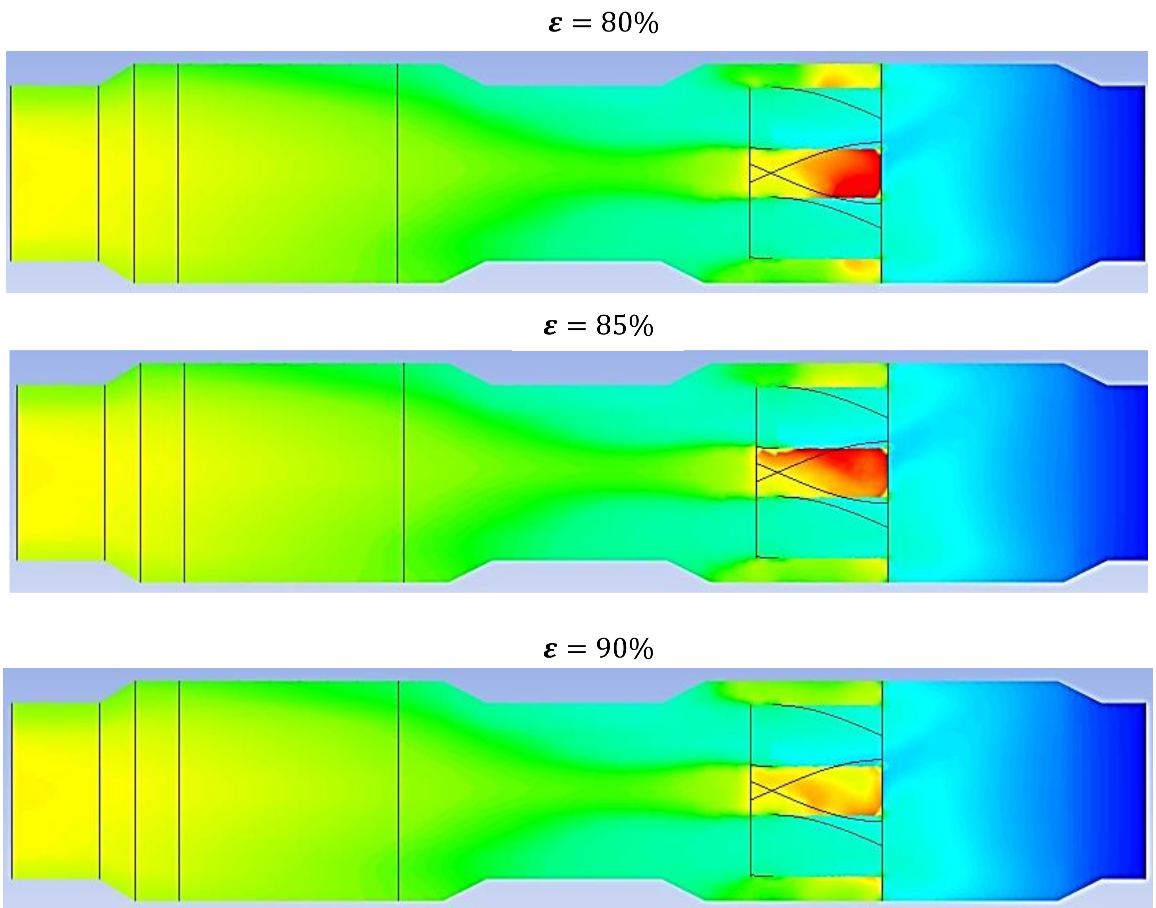
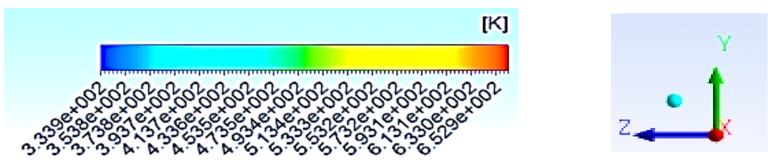



**Figure 16** The effects of the porosity on the mass fraction of carbon dioxide in the combustion chamber.

### *8.5 Increasing ambient pressure*

Variation of the diesel temperature and the mass fraction of nitrogen gas and carbon dioxide with the same amount of fuel and different initial pressures is displayed in Figs. (17) to (19). Results show that the amount of NOx pollutant is significantly reduced by increasing the ambient pressure and decreasing the maximum temperature of the combustion. The main reason behind the decrement of the maximum temperature of the combustion is that the convection coefficient and the heat transfer rate increase by increasing the ambient pressure. The rise in the ambient pressure also leads to the rise of the pumping and heat dissipation in the system, thereby increasing the specific fuel consumption. Due to the decrease in the maximum temperature, the amount of NOx pollutants decreases. That is, the maximum temperature and pressure inside the combustion chamber are the most influential factors in NOx generation during the combustion process. The amount of carbon dioxide also increases with the rise of the pressure. Therefore, the decomposition of carbon dioxide increases and more carbon monoxide is produced.



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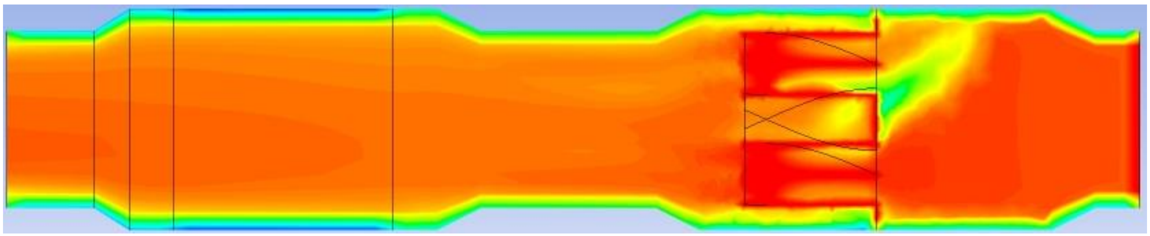

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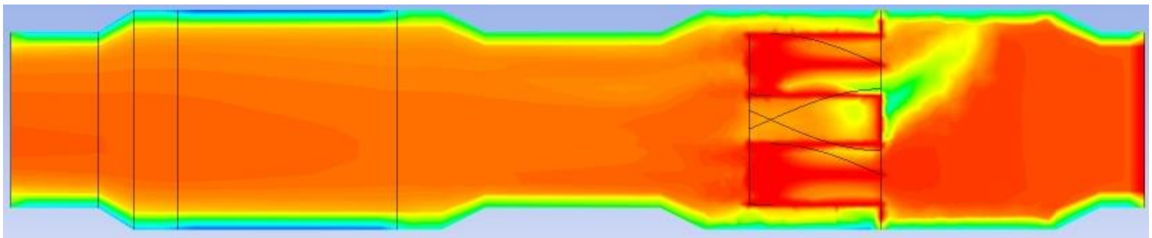

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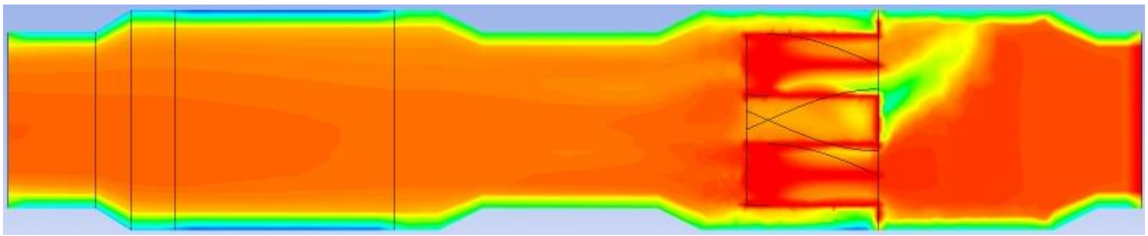
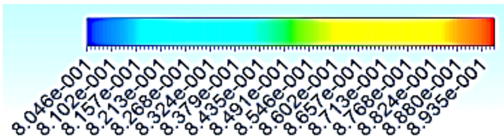
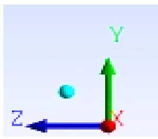


**Figure 17** The effects of increasing ambient pressure on the temperature distribution in the combustion chamber.

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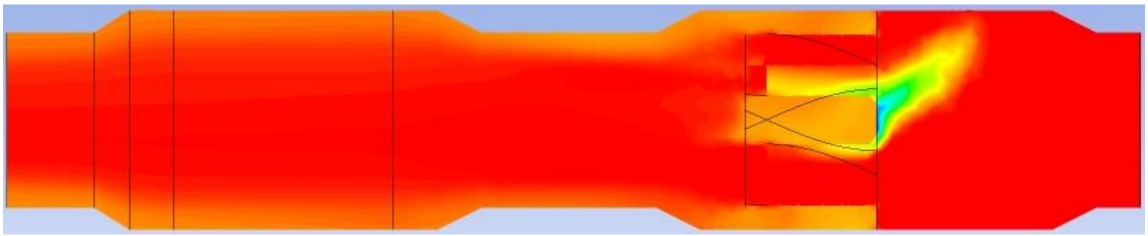

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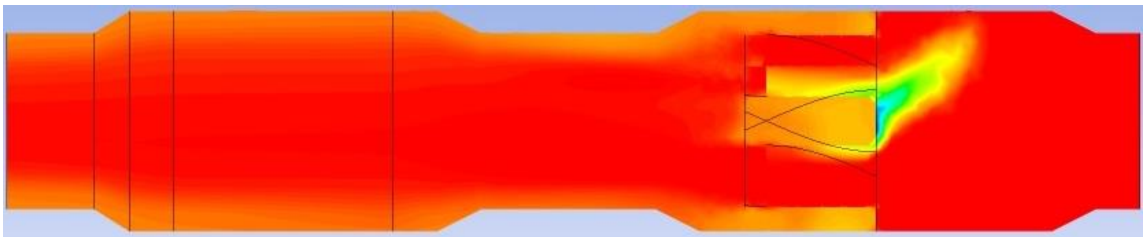

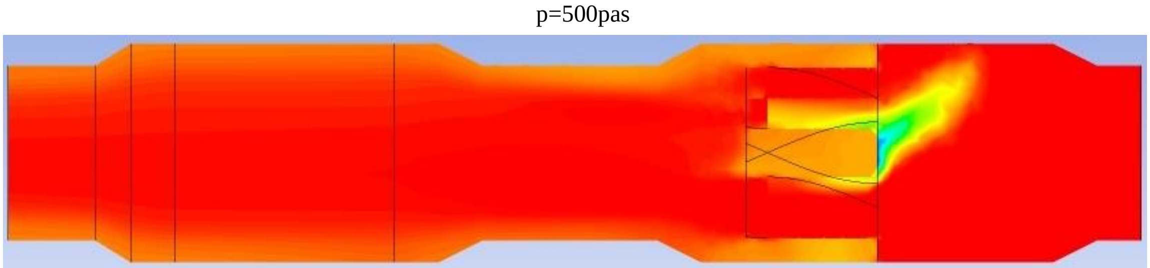


**Figure 18** The effects of increasing ambient pressure on the mass fraction of nitrogen gas in the combustion chamber.

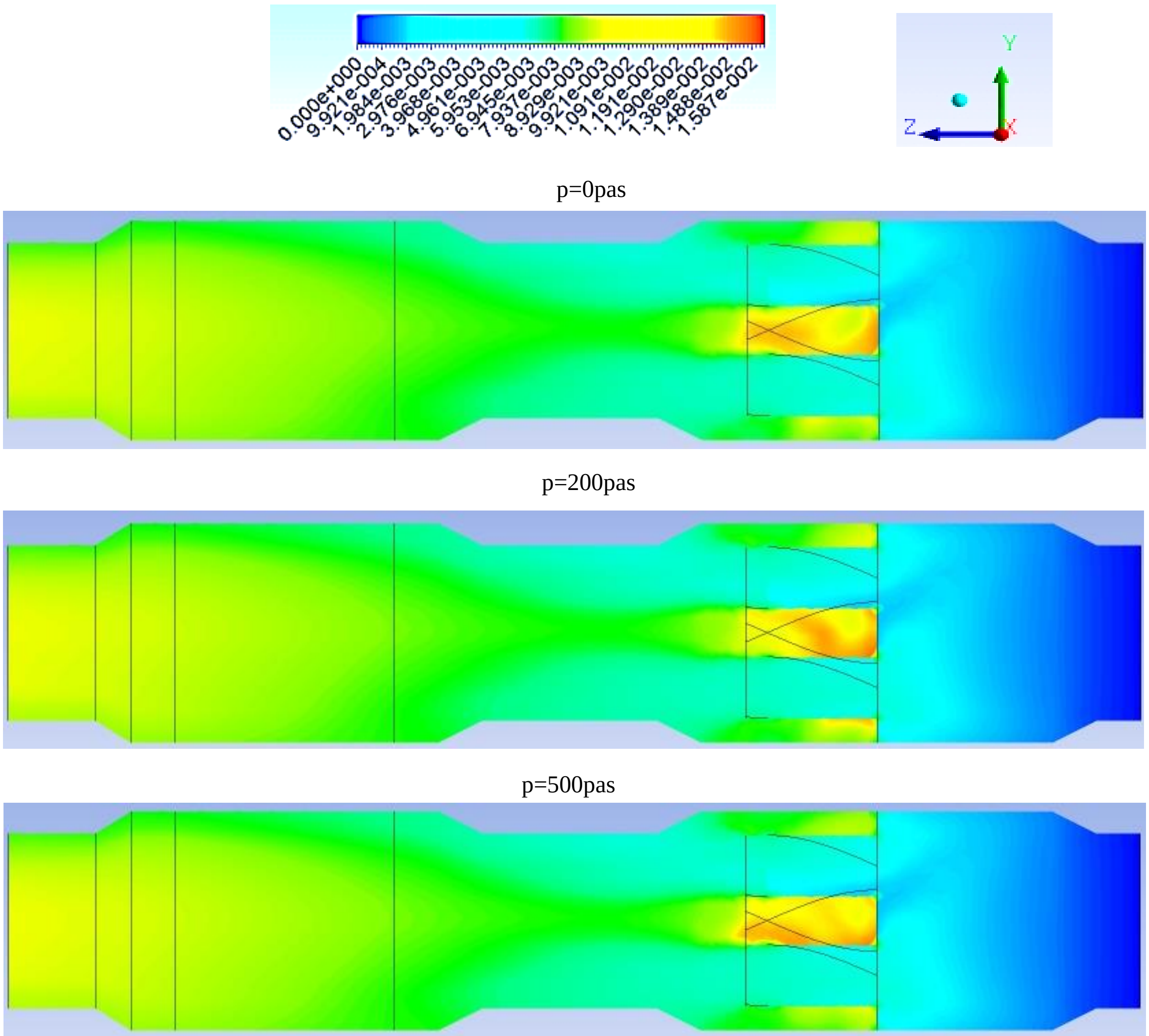


**Figure 19** The effects of increasing ambient pressure on on the mass fraction of carbon dioxide in the combustion chamber.

## 9 Conclusion

In this study, the effects of the temperature, mass flow rate of the injected fuel, pore diameter, porosity, and ambient pressure on the amount of pollutants in the combustion chamber are investigated. The main findings of the present study are as follows:

- Utilization of porous media with liquid fuel in the internal combustion engines can have promising results in terms of reducing carbon monoxide and nitrogen monoxide pollutants.

- The temperature distribution in the combustion flames is more uniform by pre-heating the air.

- The mass fraction of carbon monoxide is doubled with increasing the temperature which is mainly due to the high temperature and the breakdown of carbon dioxide molecules that are converted to the carbon monoxide.

- The amount of NOx pollutants decreases with the decrease in the maximum temperature.

- Increasing the porosity makes heat distribution more uniform along the flame which increases the thermal efficiency and decreases the fuel consumption.

- Increasing the heat transfer in porous medium leads to the decrease in the gas temperature and $NO_X$ formation.

- The production of unburnt hydrocarbon species like carbon monoxide is decreased due to a better pre-heating process in porous medium.

- Increasing the diameter of pores slightly reduces the amount of carbon monoxide since penetration of fuel droplets into the porous media occurs more easily with increasing the average diameter of pores.

- The amount of nitrogen monoxide surges up with the increase of the pore diameter.

- The mass fraction of carbon monoxide decreases with the rise of the mass flow rate of the fuel injected into the cylinder.

- The amount of NOx pollutants is significantly reduced by increasing the ambient pressure and decreasing the maximum temperature of the combustion.

- The amount of carbon monoxide increases with the rise of the ambient pressure.

**Acknowledgment**

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**References**

[1] Salvi, S., "Health Effects of Ambient Air Pollution in Children", Paediatric Respiratory Reviews, Vol. 8, No. 4, pp. 275-280, (2007).

[2] Patankar, A., and Trivedi, P., "Monetary Burden of Health Impacts of Air Pollution in Mumbai, India: Implications for Public Health Policy", Public Health, Vol. 125, No. 3, pp. 157-164, (2011).

[3] Seedam, A., Satiennam, T., Radpukdee, T., Satiennam, W., and Ratanavaraha, V., "Motorcycle On-road Driving Parameters Influencing Fuel Consumption and Emissions on Congested Signalized Urban Corridor", Journal of Advanced Transportation, Vol. 2017, pp.1-6, (2017).

[4] Kummer, J.T., "Catalysts for Automobile Emission Control", Progress in Energy and Combustion Science, Vol. 6, No. 2, pp. 177-199, (1980).

[5] Conway, R., Chatterjee, S., Naseri, M., and Aydin, C., "Demonstration of SCR on a Diesel Particulate Filter System on a Heavy Duty Application", SAE Technical Paper, Vol. 1033, No. 1, pp. 1-8, (2015).

[6] Wardana, M.K.A., Shahariar, G.M., Oh, K., and Lim, O., "Ammonia Uniformity to Predict NOx Reduction Efficiency in an SCR System", International Journal of Automotive Technology, Vol. 20, No. 2, (2019).

[7] Varna, A., Spiteri, A.C., Wright, Y.M., Eggenschwiler, P.D., and Boulouchos, K., "Experimental and Numerical Assessment of Impingement and Mixing of Urea–water Sprays for Nitric Oxide Reduction in Diesel Exhaust", Applied Energy, Vol. 157, pp. 824-837, (2015).

[8] Varna, A., Boulouchos, K., Spiteri, A., Eggenschwiler, P.D., and Wright, Y.M., "Numerical Modelling and Experimental Characterization of a Pressure-assisted Multi-stream Injector for SCR Exhaust Gas After-treatment", SAE International Journal of Engines, Vol. 7, No.4, pp. 2012-2021, (2014).

[9] Auvray, X., Partridge, W., Choi, J.S., Pihl, J., Coehlo, F., Yezerets, A., and Olsson, L., "Kinetic Modeling of NH3-SCR over a Supported Cu Zeolite Catalyst using Axial Species Distribution Measurements", Applied Catalysis B: Environmental, Vol. 163, pp. 393-403, (2015).

[10] Baleta, J., Mikulčić, H., Vujanović, M., Petranović, Z., and Duić, N., "Numerical Simulation of Urea Based Selective Non-catalytic Reduction DeNOx Process for Industrial Applications", Energy Conversion and Management, Vol. 125, pp. 59-69, (2016).

[11] Wardana, M.K.A., Oh, K., Lee, Y.J., Woo, Y.M., and Lim, O., "Effects of Urea Injection Timing on Predicting Nox Conversion in Scr Systems", International Journal of Automotive Technology, Vol. 21, No. 1, pp. 137-145, (2020).

[12] Marchitti, F., Nova, I., and Tronconi, E., "Experimental Study of the Interaction between Soot Combustion and NH3-SCR Reactivity over a Cu–Zeolite SDPF Catalyst", Catalysis Today, Vol. 267, pp. 110-118, (2016).

[13] Smith, H., Zöchbauer, M., and Lauer, T., "Advanced Spray Impingement Modelling for an Improved Prediction Accuracy of the Ammonia Homogenisation in SCR Systems", SAE Technical Paper, No. 1054, (2015).

[14] Sarafraz, M.M., Safaei, M.R., Goodarzi, M., and Arjomandi, M., "Reforming of Methanol with Steam in a Micro-reactor with Cu–SiO2 Porous Catalyst", International Journal of Hydrogen Energy, Vol. 44, No. 36, pp. 19628-19639, (2019).

[15] Sarafraz, M.M., Safaei, M.R., Goodarzi, M., and Arjomandi, M., "Experimental Investigation and Performance Optimisation of a Catalytic Reforming Micro-reactor using Response Surface Methodology", Energy Conversion and Management, Vol. 199, Article Number:111983, https://doi.org/10.1016/j.enconman.2019.111983, (2019).

[16] Durst, F., "A New Concept of IC Engine with Homogeneous Combustion in Porous Medium", The Fifth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMODIA), July 7, Nagoya, pp. 286-293, (2001).

[17] Durst, F., and Weclas, M., "A New Type of Internal Combustion Engine Based on the Porous-medium Combustion Technique", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 215, No. 1, pp. 63-81, (2001).

[18] Le, D., Chein, C., and Kwak, Y., "Improving Surface Characteristic of Porous Media Reactor in Diesel Engine by Plasma Technology", In F2006C27 Conference, (2006).)

[19] Kannan, C., and Tamilporai, P., "Smart Ceramic Materials for Homogeneous Combustion in Internal Combustion Engines-A Review", i-Manager's Journal on Future Engineering and Technology, Vol. 4, No. 1, pp. 1-8, (2008).

[20] Kannan, C., and Tamilporai, P., "Part Load Performance and Emission Improvement of Direct Injection Diesel Engine through Porous Medium Combustion Technique", Clean–Soil, Air, Water, Vol. 37 , No. 10, pp. 806-810, (2009).

[21] Kannan, C., and Tamilporai, P., "Enhancement of Emission Characteristics of a Direct Injection Diesel Engine through Porous Medium Combustion", International Journal of Energy an Environment, Vol. 2, No. 5, pp. 871-876, (2011).

[22] Saravanan, S., Kumar, R., and Edwin Geo, V., "An Experimental Study to Analyze Influence of Porous Media Combustor on Performance and Emission Characteristics of a DI Diesel Engine", Fuel, Vol. 280, pp. 118645, (2020).

[23] Zhou, L., Xie, M., Jia, M., and Shi, J., "WITHDRAWN: Numerical Study on Combustion and Emission Characteristics of a Regenerative Porous Medium (PM) Engine", https://doi.org/10.1016/j.apenergy.2009.12.020, Applied Energy, (2010).

[24] Park, C.-W., and Kaviany, M., "Evaporation-combustion Affected by In-cylinder, Reciprocating Porous Regenerator", Journal of Heat Transfer, Vol. 124, No. 1, pp. 184-194, (2002).

[25] Zhao, Z., and Xie, M., "Numerical Study on the Compression Ignition of a Porous Medium Engine", Science in China Series E: Technological Sciences, Vol. 51, No. 3, pp. 277-287, (2008).

[26] Ge, Y., Chen, L., and Sun, F., "Thermodynamic Modeling and Parametric Study for Porous Medium Engine Cycles", Termotehnica , Vol. 13, pp. 49-55, (2009).

[27] Dhale, A.A., Awari, G.K. , and Singh, M.P., "Analysis of Internal Combustion Engine with a New Concept of Porous Medium Combustion for the Future Clean Engine", Thermal Science, Vol. 14, No. 4, pp. 943-956, (2010).

[28] Nova, I., and Tronconi, E., "*Urea-SCR Technology for DeNOx after Treatment of Diesel Exhausts*", Springer, New York, (2014).

## Nomenclature

| | |
|---|---|
| $c_1, c_2, c_3$ | Constant |
| $C_2$ | Inertial resistance coefficient |
| $d_p$ | Pore diameter (m) |
| $e_s$ | Energy ($kgm^2s^{-2}$) |
| F | Force (kg $ms^{-2}$) |
| k | Turbulent kinematic energy ($m^2s^{-2}$) |
| $m_p$ | Mass of particles (kg) |
| $m_p \frac{\vec{u}-\vec{u_p}}{\tau_r}$ | Drag force |
| $\dot{m}$ | Mass flow rate of the injected fuel ($kgs^{-1}$) |
| p | Pressure ($kgm^{-1}s^{-2}$) |
| Re | Relative Reynolds number |
| $S_i$ | Source term ($kgm^{-3}s^{-1}$) |
| T | Temperature (K) |
| t | Time (s) |
| $u_i, u_j, u_k$ | Mean velocity components ($ms^{-1}$) |
| $\vec{u}$ | The fluid phase velocity ($ms^{-1}$) |
| $\vec{u_p}$ | Velocity of particles ($ms^{-1}$) |
| x | Along stream wise direction (m) |
| y | Normal direction(m) |
| α | Permeability ($m^2$) |
| ε | Turbulent dissipation rate ($m^2s^{-3}$) |
| ε | Porosity |
| μ | Dynamic viscosity($kgm^{-1}s^{-1}$) |
| $\mu_{eff}$ | Effective viscosity ($kgm^{-1}s^{-1}$) |
| ϑ | Kinematic viscosity ($m^2s^{-1}$) |
| ρ | Fluid density ($kgm^{-3}$) |
| $\rho_p$ | Density of particles ($kgm^{-3}$) |
| $\tau_r$ | Relaxation time of particles (s) |

*Abbreviations*

| | |
|---|---|
| CO | Carbon monoxide |
| DPM | Discrete phase model |
| FVM | Finite volume method |
| ICEs | Internal combustion engines |
| NOx | Nitrogen oxides |
| WHO | World Health Organization |