

Effect of Fuel Inject Angle on the Thermal Behavior of a 2D Axisymmetric Non-Premixed Methane-Air Flame in Vertical Cylinder Filled by Porous Media

M.Y. Abdollahzadeh Jamalabadi^{*1}, Moein Rajabzadeh², P. Hooshmand³

¹Maritime University of Chabahar, Chabahar, Iran

²Babol Noshirvani university of Technology, Department of Mechanical Engineering, Babol, Iran

³Young Researchers and Elite Club, Mahabad Branch, Islamic Azad University, Mahabad, Iran

^{*1}muhammad_yaghoob@yahoo.com; ^{*1}my.abdollahzadeh@gnu.ac.kr

Abstract-The present manuscript is dedicated to the study of non-premixed combustion within a vertical cylinder filled by inert porous media using a turbulence model. A study of the effect of inlet gas angle on methane/air combustion is performed. Governing equations of Navier-Stokes, energy and the chemical species transport equations in a porous media with local thermal non-equilibrium assumption between the solid and fluid are solved. Distinct energy equations are considered for the porous burner and the fuel in it. Inlet velocity and excess air-to-fuel ratio are varied in order to analyze their effects on temperature, turbulent kinetic energy distribution and flame front location. The temperature field and species concentrations are presented in the premixed methane - air combustion. The results show that an increase in angle of inlet gas enhances the mixing rate, the peak temperature, and water and carbon dioxide volume fraction inside the middle region of the chamber. The locations of the maximum temperature and product concentration shift closer to the combustor inlet with an increase in inlet angle. Furthermore, the temperature in porous burners is lower than free flame burners, and lower NO_x and CO pollutant are achieved.

Keywords- Methane/Air Flame; Turbulent Model; Numerical Simulations; Non-Premixed; Porous Media

I. INTRODUCTION

In coal furnaces, diesel internal-combustion engines and pool fires there is non-premixed combustion, in which there are two distinct streams of fuel and oxidizer before burning [1]. In recent years, many researchers have investigated the porous media combustion technology both experimentally and theoretically. The most of researches are in the field of steady combustion in porous media and few of them are about transient flame propagation, both approaches are employed in porous media combustion [2-3]. Steady combustion is widely used in radiant burners and surface combustor-heaters due to its high radiant emissivity of the solid. The combustion zone is stabilized by its solid while transient flame leads to an unsteady reaction zone freely propagating as a filtration combustion wave in the downstream direction [4-6]. Combustion in porous media differs considerably from the homogeneous flames front. Considerable features of porous media for application of combustion technology are large specific surface area, excellent heat transfer properties, heat capacity, transparency for fluid flow, thermal resistance, mechanical resistance, recuperation of energy and electrical properties. Generally the non-premixed combustion flames contain locally fuel-rich regions that are the all set for the pollutant productions due to lack of oxidizer. In those regions products yield larger hydrocarbons instead of carbon dioxide and water [7-10]. The soot formation is sturdily hooked to the fuel concentration and temperature [4-5]. In non-premixed flames, the fuel and oxidant are initially separated, and the combustion is measured by diffusion and turbulence. Combustion problems include numerous coupled phenomena, such as fluid mechanics, heat transfer, and chemical kinetics of gaseous species and soot. Heat transfer directly affects the temperature field and the chemical kinetics is strongly dependent on temperature [11-15]. On the other hand, modeling thermal combustion gases through porous media (such as water vapor and carbon dioxide) is a difficult task due to the highly complex dependence of the exchange coefficient with the location, which is typically characterized by hundreds of thousands or millions of pores [16-22].

In some combustion chambers in laminar and simple turbulent jet diffusion flames, the injectors located in the manifold and the fuel are injected along with the angle of the injector and the spray characteristics of the injectors are important to obtain the optimum combustion performances. The results of numerical modeling of direct axisymmetric turbulent methane-air simple jet (without swirl) flames are present in many numerical studies which normally have shown a good agreement with the experimental measurements [23-26]. Effect of fuel flow direction is useful in many technical applications, particularly in furnaces and gas turbines to improve the characteristics of flame stabilization, ignition stability, mixing enhancement, pollutant reduction and blow-off [27-30]. The major target for further development of the current IC engines is to reduce their harmful emissions to the environment. The most important difficulty with existing IC engines is the non-homogeneity of mixture formation within the combustion chamber. This non-homogeneity is the cause of heterogeneous heat release and high temperature gradient in combustion chamber. In addition that is the main source of excess emissions such as NO_x, unburned hydrocarbons (HC), carbon monoxide (CO), soot and suspended particles [31-32].

At present, the IC engine exhaust gas emission could be reduced by catalyst, but it's costly, sensitive to fuel and with low efficiency. Another strategy has been initiated to avoid the temperature gradient in IC engines using homogeneous charge compression ignition (HCCI). Although the effect of many parameters on combustion of air/methane mixtures has been investigated by many investigators, but few researches are performed from the perspective of the influence of the injection angle strategies on combustion processes which have been reported [34-35]. Also the effects of surface thermal radiation which are important in other fields are not considered [11-14]. Combustion in inert porous media has been extensively investigated due to many engineering applications and demands for developing high-efficiency power production devices. The growing use of efficient radiant burners can be found in the power and process industries and, as such, proper mathematical models of flow, heat and mass transfer in porous media with combustion can benefit the development of such equipment. The advantages of having a combustion process inside an inert porous matrix are today well documented in the literature [1-4].

The aim of this paper is to study the effect of fuel injection angle on fluid, mass transfer, and thermal characteristics of a methane/air flame in turbulent diffusion flames at vertical cylindrical porous combustor. Computations are carried out for inert porous material considering two-dimensional geometry and a model of two energy equations without radiation.

II. COMPUTATIONAL DOMAIN

A common fuel injection valve of a combustion chamber includes a concave conical surface, fuel injection holes in its surface, and a portable needle valve. But here that valve is not modelled through the combustion chamber and just its effect on the fuel injection angle is considered. As shown in Fig. 1, a vertical combustor with a circular cross-section is assumed to confine the flame and prevent gas composition fluctuations subsequent from the ambient air. The combustion chamber is 25 cm in diameter (D) and 100 cm in length (L). A hole with 1 cm diameter (d) at the centre is used to deliver the fuel (CH_4) with the velocity magnitude of 80 m/s to the burner and the air ($0.23 \text{ O}_2 \text{ } 0.77 \text{ N}_2$) enters from the annulus between that hole and burner with the velocity of 20 m/s. The fuel injection angle is measured from the axis of symmetry of the combustion chamber. The wall and inlet hold at environment temperature (300 K).

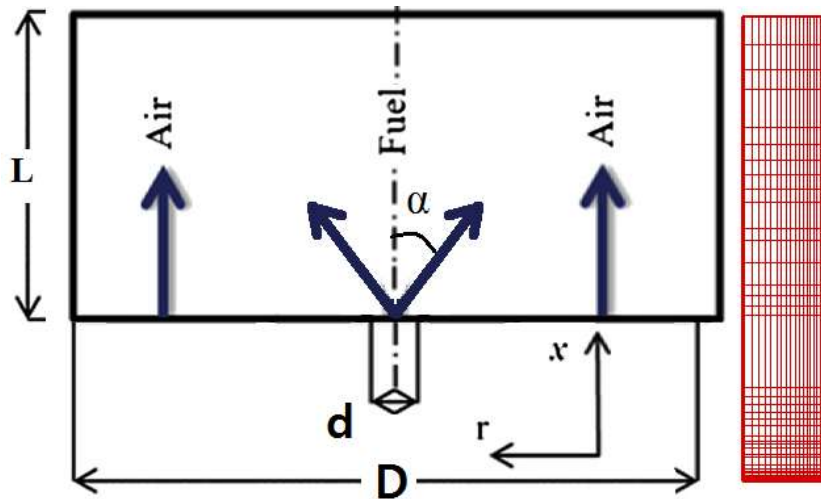


Fig. 1 Schematic of the vertical cylinder combustion chamber and the computational mesh

III. MATHEMATICAL MODELLING

In this study, the combustion will be modeled assuming complete conversion of the fuel to CO_2 and H_2O . The mass, momentum, energy, and species conservation equations are the governing equations. The equation for conservation of mass or continuity equation can be written as

$$\frac{\partial \rho \phi u}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (\rho \phi r v) = 0 \quad (1)$$

x and r are the axial and radial coordinates [m], u and v are the velocities in these respective directions [m/s] and ϕ is the porosity of the medium.

Conservation of momentum in fluid is described by

$$\frac{1}{r} \left[\frac{\partial}{\partial x} (r \rho \phi u u) + \frac{\partial}{\partial r} (r \rho \phi u v) \right] = -\frac{\partial p}{\partial x} + \mu \nabla^2 u - \frac{1}{r} \frac{\partial}{\partial r} (r \rho \phi u' v') - \frac{\partial}{\partial x} (\rho \phi u' u') + F_x \quad (2)$$

$$\frac{1}{r} \left[\frac{\partial}{\partial x} (r \rho \phi u v) + \frac{\partial}{\partial r} (r \rho \phi v v) - \rho \phi v^2 \right] = -\frac{\partial p}{\partial r} + \mu (\nabla^2 v + \frac{v}{r^2}) - \frac{1}{r} \frac{\partial}{\partial r} (r \rho \phi \overline{v'v'}) - \frac{\partial}{\partial x} (\rho \phi u'v') + F_r \quad (3)$$

Where τ is the stress tensor, and F is an external body force. F also contains other model-dependent source terms such as porous-media. The turbulent stresses are calculated from an algebraic stress model and wall-function approach is used in the near-wall. ρ is the density of the gaseous mixture [kg/m^3], μ is the gaseous mixture dynamic viscosity, and μ_t is the turbulent viscosity [Ns/m^2], C_1 is an empirical constant of the turbulence model ($C_1 = 0.09$), p is the combustion chamber operational pressure ($p = 101325 \text{ Pa}$), and k and ε are the turbulent kinetic energy and its dissipation. T is the temperature of the gaseous mixture [K]. The energy equation in fluid is given by

$$\frac{1}{r} \left[\frac{\partial}{\partial x} (r \rho u \phi h) + \frac{\partial}{\partial x} (r \rho v \phi h) \right] = \Gamma_h \nabla^2 h - \frac{1}{r} \frac{\partial}{\partial r} (r \rho \phi v' h') - \frac{\partial}{\partial x} (\rho \phi u' h') + \dot{S}_h + H(T_s - T_f) \quad (4)$$

Where Γ_{eff} is calculated from the effective conductivity of the porous medium (and considering the turbulent thermal conductivity defined according to the turbulent model used), and H is the heat flux coefficient between phases ($\text{Nu} = 2 + 1.1 \text{Re}^{0.6} \text{Pr}^{0.33}$). The first three terms on the right hand side represent energy transfer due to conduction, species diffusion, and viscous dissipation respectively. Also, h is calculated from the total energy defined for ideal gas which is incompressible as a function of the mass fraction of each species. For many multicomponent mixing flows, the transport of enthalpy due to species diffusion can have a significant effect on the enthalpy field and should not be neglected. In particular, when the Lewis number for any species is far from unity, neglecting this term can lead to significant errors. The reaction rates that appear as source terms in the species transport equations are computed from Arrhenius rate expression, from the eddy dissipation model. Also, $C_{1,e}$ and $C_{2,e}$ are empirical constants of the turbulence model ($C_{1,e} = 1.44$ and $C_{2,e} = 1.92$), σ_k and σ_ε are the Prandtl numbers of the kinetic energy and dissipation, respectively ($\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$). The last term \dot{S}_h is heat of chemical reactions. Pr_i and Sc_i are the turbulent Prandtl and Schmidt numbers, S_j [$\text{kg}/(\text{m}^3 \text{ s})$] is the volumetric rate of energy formation or consumption of the j th chemical species (CH_4 , O_2 , CO_2 , CO , H_2O). By the assumption, that the thermal non-equilibrium between gas and solid phases and solid is homogeneous, isotropic, having variable property with temperature and having no catalyst effects, the energy equation in solid is given by

$$0 = (1 - \phi) \Gamma_s \nabla^2 T_s + H(T_f - T_s) + \nabla \cdot \left(\frac{16\sigma}{3\chi} T_s^3 \nabla T_s \right) \quad (5)$$

And also the mass conservation equation for species transports is given by

$$\frac{1}{r} \left[\frac{\partial}{\partial x} (r \rho u m_j) + \frac{\partial}{\partial r} (r \rho v m_j) \right] = \Gamma_{mj} \nabla^2 m_j - \frac{1}{r} \frac{\partial}{\partial r} (r \rho v' m_j') - \frac{\partial}{\partial x} (\rho u' m_j') + R_j \quad (6)$$

Where R_j is the net rate of production of species j due to chemical reaction and the turbulent terms calculated from the Schmidt number, the turbulent viscosity and the turbulent diffusivity by the standard two-equation, $k - \varepsilon$ turbulence model are employed in this study. In addition to the conservation laws, an equation of state is required to calculate the mixture density by considering the mixture of fuel, oxidant and products as an ideal gas. The computational mesh of the half of the burner with boundary layer meshes the inlet and the axis of symmetry is illustrated in Fig. 1. The grid resolution is high at the locations where gradients of variables are high. The control volume approach, or the finite-difference method, can be used to solve the governing equations. The solution is advanced in time by using a fully implicit technique and this is necessary due to the stiffness of the governing matrix of the problem. Also, it is necessary to use an adaptive grid or a very fine grid to insure the accuracy of the solution.

TABLE 1 SOLID PROPERTY DATA USED FOR REFERENCE CASE COMPUTATION

Pore Diameter	0.029 cm
Porosity	0.835
Conductivity	1.6 W/mK
χ	270 1/m
Density	510 kg/m^3
Specific heat	824 J/kg K

Alumina is used as a porous burner material because of its durability, high temperature rating, chemical stability, and economic cost. Previous theoretical and experimental studies have investigated materials including 10 and 66 pores per inch (PPI) Al_2O_3 , 45 PPI ZrO_2 that is partially stabilized with magnesia (PSZ) and 10 or 20 PPI Al_2O_3 foam burners, and a combination of 10 and 40 PPI Al_2O_3 . Flame can easily be stabilized at the interface between two ceramic blocks with different porosities because of radiative heat feedback. Flame stability decreased with increased pore density of Al_2O_3 sponges. The apparatus comprised a porous burner, a supply system of fuel/air, and a system for data acquisition. The burner wall was insulated by a 20 mm-thick Kaowool high-temperature insulation material layer. Methane (99.5% pure) and air flows were regulated to satisfy the required conditions at a fixed equivalence ratio. All the properties for the solid material used in the

reference case are summarized in Table 1.

IV. RESULTS AND DISCUSSION

The conservation equations are solved by using the OpenFOAM with the method described in [15]. Finite volume equations are derived by the integration of above differential equations over finite control volumes taken together fully to cover the entire domain of interest. These control volumes are called "cells" P, for which the fluid-property value, are regarded as representatives of the whole cell. It is surrounded by neighbouring nodes which we shall denote by N, S, E, and W. Cells and nodes for velocity components are "staggered" relative to those for all other variables. Finally, the continuity and momentum equations should be considered for the calculation of velocity and pressure field. For numerical reasons, it is recommendable to resort to so-called staggered grid, i.e. pressure and velocity should calculate on computational grids shifted related to each other. For example the pressure is in the centre of the cell and the velocity is on the boundary nodes.

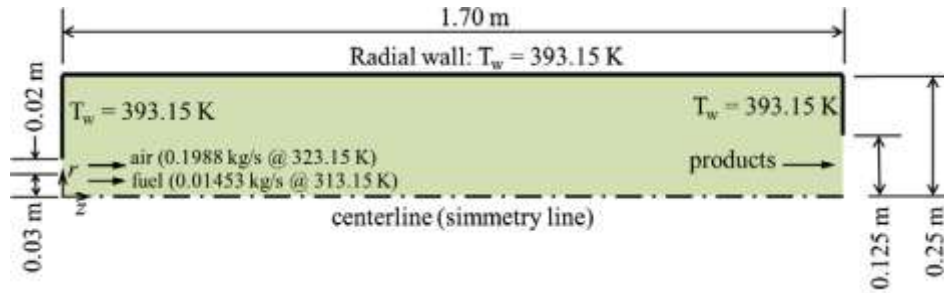


Fig. 2 Combustion chamber geometry for experimental benchmark [16]

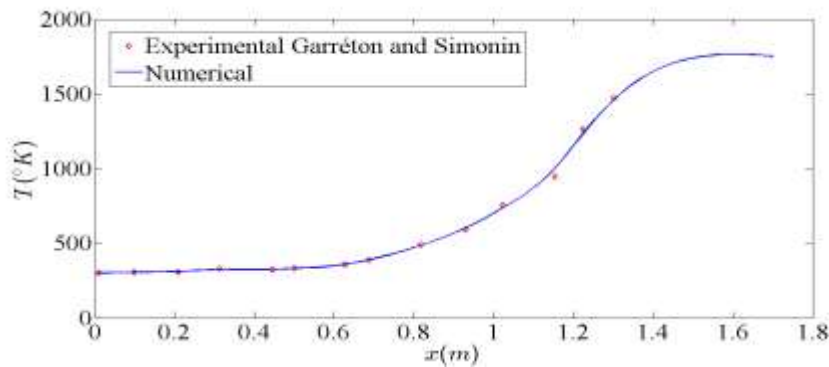


Fig. 3 Benchmark of the results with the experimental results [16]

The calculations of velocity commonly take place iteratively, for which several algorithms are known (e.g. SIMPLE, PISO, SIMPLER...). In final analysis, what all have in common is that in the first step, the momentum equation is solved for the velocities of momentums keeping constant. In the second step, pressure corrections are then calculated with the help of a Poisson equation. With these pressure corrections, new velocities are then calculated again, and that again, until a pre-given break off threshold for the convergence is reached. This part reports a two-dimensional numerical modelling of premixed methane/air combustion in porous media. To this end, OpenFOAM is used along with its database. This code solves the Navier-Stokes, the solid and gas energy and the chemical species transport equations using finite volume method. The pressure and velocity are coupled with the SIMPLE algorithm. The burner under study is a cylindrical. Fig. 2 shows the chamber geometry for experimental benchmark and the Fig. 3 shows the comparison of the current study with experimental results.

Fig. 4 shows the simulated contours of axial and radial velocities, stream function, for the cases with and without considering the porous medium. As shown by using porous the radial velocity increased and a back flow on the outlet appeared. Fig. 5 shows the simulated contours of water (H_2O), carbon dioxide (CO_2), and nitrogen (N_2) mass concentrations inside the combustor for fuel injection parallel to the axis of the burner. In what follow, the distributions of mass fractions are depicted in Fig. 5. CH_4 is consumed due to combustion. In both cases, CH_4 is highly concentrated near the fuel jet entrance while CH_4 is distributed more widely in porous domain than in the gas-phase domain. However, it can be noticed that more CH_4 is consumed for the gas phase combustion. As shown above, the radial velocities are in the one tenth orders of the axial velocities, and stream function generally is parallel to the axis of the combustion chamber. The mass concentrations of the oxygen (which is not shown here) are similar to the nitrogen and generally are divided into two regions of inlet and chemical reactions. The most of the nitrogen exited from the cavity near the wall and the minimum amount was occurring at its axis. The fuel is consumed in the small region near the inlet and for the products of the reaction (water and carbon dioxide) there are three regions in the chamber. They are zero at air inlet, a maximum at the outlet near the wall of the chamber and in moderate concentration in other sides. The results show that an increase in injection angle leads to creating the three regions for the

water and carbon dioxide in the chamber which are zero at air inlet, a maximum in the middle of the chamber and in moderate concentration in other sides. Because there is not a great change in the pressure inside the chamber and contours are not presented here. Finally, the distributions of mass fraction of combustion product CO_2 are depicted in Fig. 5. It can be observed CO_2 is more concentrated where concentrations of CH_4 are less as CH_4 is being consumed to produce CO_2 . Moreover, CO_2 is distributed more widely in porous domain than in the gas-phase domain. As shown by the use of PM the maximum reaction rate zone is brought to the left and a breathing zone at the outlet is produced.

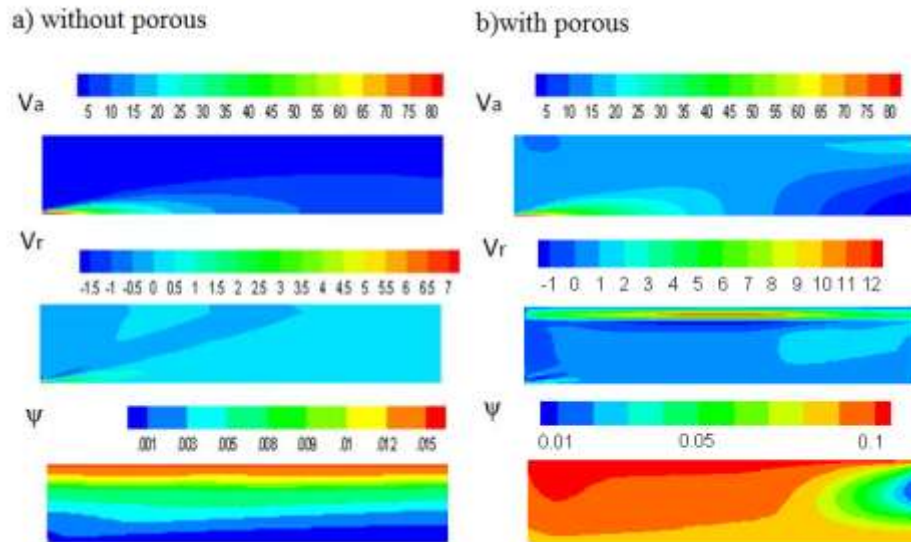


Fig. 4 Axial and radial velocities, stream function a) without and b) with porous media

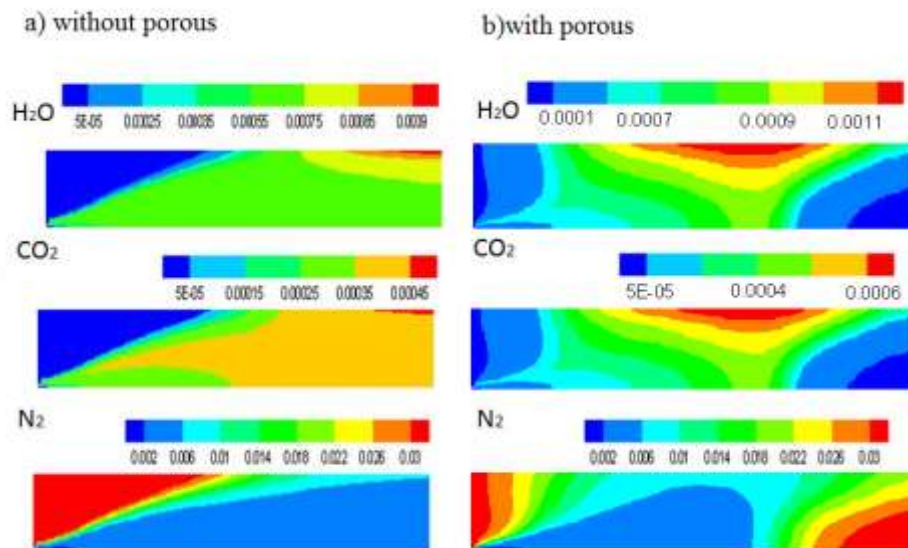


Fig. 5 Axial and radial velocities, stream function, H_2O , CO_2 , N_2 mass concentrations

To get more insight in species transport phenomena, Fig. 6 shows the vorticity distribution at fuel injection parallel to the combustion chamber axis for gas phase and porous. As illustrated the maximum of the vorticity occurs in the methane inlet because of the high mixing of the fuel and oxidizer. The porous case gave lower average value of stream function which implies lower flow intensity. This result is attributed to the viscous effect of solid boundaries within the porous structure. As shown by the use of PM the maximum vorticity increases but the average vorticity decreases.

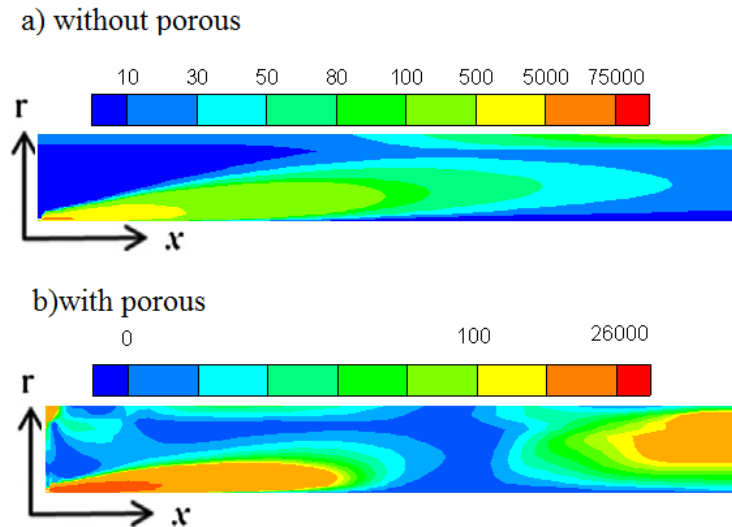
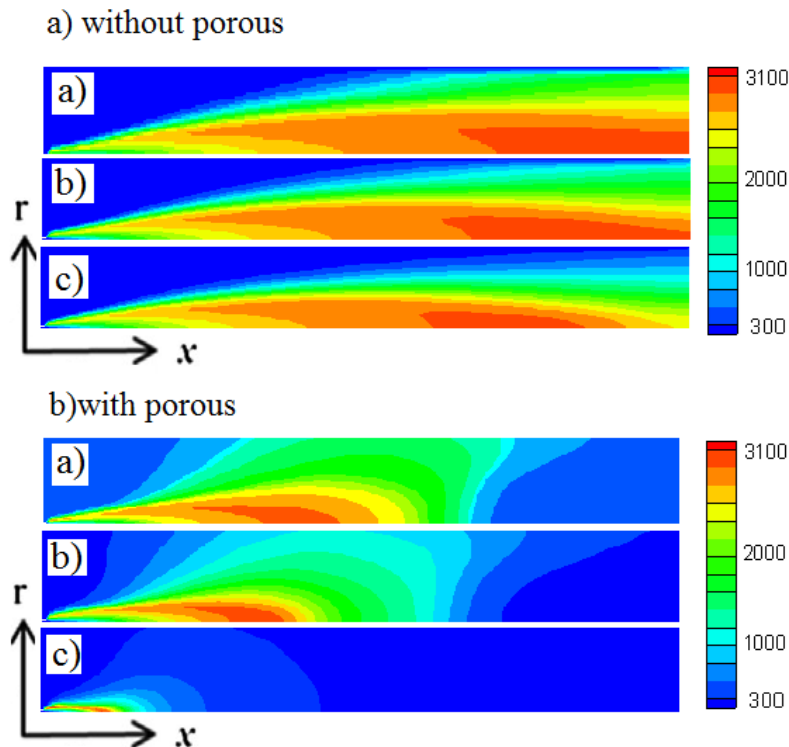
Fig. 6 Vorticity contour at $\alpha=0$

Fig. 7 shows the temperature distribution caused by heat release at various fuel injections in case of porous combustion. Because the cylinder pressure is mostly constant, it is not shown here. As illustrated the increase of the inject angle increases combustion efficiency, due to enhancement of mixing rates between the fuel and oxidant and augment the combustor peak temperature. However, the variation for the first injection is slightly higher. Furthermore, the increase of the inject angle makes the combustion zone of the diffusion flame enlarge and the location of the maximum temperature shift inside the chamber. In addition, for the narrower-angle injector, fuel jets are restricted to a smaller region than the wider-angle injectors, and the mixing would be less homogeneous. The computed temperature is shown in Fig. 7 for the gas phase combustion of pure air and CH_4 . It can be seen in the figure that temperature is very high in the place where the intense reactions take place. The flame propagates towards the downstream while it spreads from the symmetrical line of the computational domain. The temperature is found lower while temperature contour spreads out more widely. This is attributed to the fact that a porous medium has a feature of combusting sub-normal lean mixtures due to intense heat transfer across the solid to preheat the mixture to the temperatures that sustain chemical reactions. The results are consistent with the temperature distribution shown in Fig. 7. More consumptions of CH_4 indicate a higher rate of reaction causing greater temperature rise. As is shown that the use of PM the maximum temperature decreases (from the order of 3100 to 2800, 2600, and 2200 respectively) and the location of maximum temperature comes to the left.

Fig. 7 Temperature contours at various fuel injection angle a) $\alpha=0^\circ$ b) $\alpha=45^\circ$ c) $\alpha=80^\circ$

V. CONCLUSIONS

Numerical simulations of methane diffusion combustion in porous burner have been successfully carried out. Several computed field variables considered include temperature, stream function, and species mass fractions. The analysis has been done through a comparison with the gas-phase combustion. Porous combustion is found to give lower temperature with more uniform distribution throughout the domain. In addition, porous combustion provides a greater rate of fuel consumption thereby raising peak temperature. The porous combustion in a burner is proved wider flame stability limits and can hold an extended range of firing capabilities due to an energy recirculation. Burning behaviours of non-premixed methane-air flame are studied for different fuel injection angles. As shown, the fuel injection angle is an efficiency parameter to control the fluid flow and combustion characteristics through the combustion chamber. The addition of Porous leads to an increase of the combustion temperature, and it causes an increase in the rate of produced NO, because most of the produced NO is a thermal NO, the amount of produced CO and CO₂ decreases, and the overall rate of carbon in the methane/hydrogen mixture is reduced. Furthermore, the optimum fuels inject angle leads to the reduction of the burned gas velocity for the same jet velocity of methane/hydrogen mixture. As shown by the use of PM the maximum temperature decreases (from the order of 3100 to 2800, 2600, and 2200 respectively) and the location of maximum temperature comes to the left. Furthermore the maximum vorticity increases but the average vorticity decreases because the maximum reaction rate zone is brought to the left and a breathing zone at the outlet is produced.

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M. Y. Abdollahzadeh Jamalabadi is an assistant professor at the Chabahar Maritime University. He received his B. Sc. in Fluid mechanical engineering from Iran university of Science and technology in 2006, Master's Degree in energy conversion from Sharif University of technology in 2008, and his Ph.D. degree in Mechanics from Khajeh Nasir Toosi University in 2012. His research interests include fluid flow simulation, CFD, MHD, heat transfer, thermal radiation, and SOFC simulation. Now he is a senior research scientist at the Gyeongsang National University.