# EFFECT OF THERMAL RADIATION ON NON-PREMIXED COMBUSTION OF AIR/METHANE MIXTURES IN VERTICAL POROUS CYLINDER

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**ABSTRACT**

The present work is the numerical study of non-premixed combustion within a vertical porous cylinder using turbulence model with various angle of fuel injection with and without thermal radiation effects. In such a problem, two aspects need to be considered for a precise evaluation of the thermal radiation: the turbulence–radiation interactions, and the local variation of the radiative properties of the participating species, which are treated here with the weighted-sum-of-gray-gases model. The chemical reactions rates were considered as the minimum values between the Arrhenius and Eddy Break-Up rates. A two-step global reaction mechanism is used, while the turbulence modeling was considered via standard k–ε model. The source terms of the energy equation consisted of the heat generated in the chemical reaction rates as well as in the radiation exchanges. The discrete ordinates method is employed to solve the radiative transfer equation. Comparisons of simulations with/without radiation demonstrated that the temperature, the radiative heat source, and the wall heat flux were importantly affected by thermal radiation, while the influence on species concentrations proved to be negligible. The results show the importance of thermal radiation for an accurate prediction of the thermal behavior of a combustion chamber. The governing equations: continuity, axial momentum, radial momentum, turbulent kinetic energy, turbulent kinetic energy dissipation, energy, CH4, O2, CO2, CO and H2O mass fraction. The results show that $CO_2$ is not a passive diluent and can also interact through radiative transfer and this radiation effect is very significant. In addition, an increase in angle of inlet gas enhances the mixing rate, 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 increase in inlet angle.

**Keywords:** *Methane/air Flame, Turbulent model, Numerical simulations, Non-premixed, turbulent combustion, porous media.*

**Nomenclature**

| | |
|---|---|
| d | fuel injection hole diameter (m) |
| $D$ | burner throat diameter (m) |
| $G_\phi$ | axial flux of angular momentum (kg.m$^2$.s$^{-2}$) |
| $G_x$ | axial flux of linear momentum (kg.m.s$^{-2}$) |
| $h$ | enthalpy (j.kg$^{-1}$) |
| $m$ | mass fraction |
| $M$ | mass density (kg.m$^{-3}$) |
| $N$ | particle number density(m$^{-3}$) |
| $N_A$ | Avogadro's number |
| $r$ | radial direction (m) |
| $R$ | universal gas constant (j.kg$^{-1}$.k$^{-1}$) |
| $R_j$ | reaction rate mass of the $j$ th species |
| $\dot{S}_h$ | energy conservation equation source term |
| $T$ | mean temperature (k) |
| $u$ | axial velocity component (m.s$^{-1}$) |

| | |
|---|---|
| $v$ | radial velocity component ($m.s^{-1}$) |
| $w$ | swirl velocity ($m.s^{-1}$) |
| $W$ | molecular weight ($kg.kmol^{-1}$) |
| $x$ | axial direction (m) |
| *Greek letters* | |
| $\mu$ | molecular viscosity of gas phase ($kg.m^{-1}.s^{-1}$) |
| $\rho$ | gas phase density ($kg.m^{-3}$) |
| $\eta$ | collision efficiency of soot particles |
| $\Gamma mj$ | laminar exchange coefficient |

## 1. INTRODUCTION

In recent years, advancement of technology from micro [1] to nanoscales [2], many theoretical phenomena have found their importance in emerging applications. 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 [1-2]. Resistance of the flow of fluids through simple and complex porous media whose matrices are composed of randomly packed spheres is interested because usually the non-premixed combustion flames contain locally fuel-rich regions where because of lack of oxidizer is the all set for the pollutant productions [3]. At those regions products yield larger hydrocarbons instead of being to carbon dioxide and water and the soot formation is sturdily hooked on on the fuel concentration and temperature. So the highly porous media can be used to control the combustion [4].

In some combustion chambers in laminar and simple turbulent jet diffusion flames the injectors located in the manifold and the fuel is injected along with the angle of the injector and the spray characteristics of the injector is important to obtain the optimum combustion performances. As well as the onset of turbulence in a regular porous medium is important in fluid modeling [5-6] some studies assume the turbulent models to obtain more precise temperature distribution and mass fraction of chemical species [7]. The results of numerical modeling of directed axisymmetric premixed turbulent flames within non-homogeneous porous ceramics [8] are presented in many numerical studies which normally have showed good agreement with the experimental measurements [9-11].

Effect of fuel flows direction is useful in many technical applications particularly in furnaces and gas turbines which can be used to improve flame stabilization [12], ignition stability [13], mixing enhancement [14], pollutant reduction [15] and blow-off characteristics [16]. Combustion in porous media happens under the influence of the geometric parameters, thermo physical and thermochemical properties, and flow, heat and mass transfer conditions [17-20]. Those studies assumed mediums with local thermal and chemical non-equilibrium to design of many processes and systems [21-24]. Studies on the effects of heat transfer characteristics on the rate of burning and flame structure [25], by numerical solution of two-dimensional model on a two layer multi-step porous furnace, the effects of adding hydrogen on methane combustion in furnaces were analyzed. The effects of the properties of porous materials such as volumetric heat transfer coefficient and diffusivity on flame stability were investigated [26-28], and the multi-step chemical kinetics effects on cellular fuel combustion and pollutant formation were studied. Also many numerical modeling were conducted to predict the thermal efficiency, temperature distribution and pressure drop using multi chemical mechanism [29-30]. As the effects of geometry, pore size, thermal conductivity, and the thermal conductivity ratio on burning rate is performed. The effects of excess air emissions on temperature distribution were investigated [31]. Consideration of and radiation parameters of the solid phase is assumed within some studies [32].

The numerical simulation [33-37] of combustion processes involves the coupled solution of complex phenomena, such as turbulent fluid flow [38-45], chemical kinetics [46-51] of gaseous species and soot, and combined convection–radiation heat transfer [52-58]. Natural gas, which mainly consists of methane, offers considerable economic and environmental advantages such as improved efficiency, availability, and pollutant emissions and is commonly used in several applications [59-63]. Methane can reach to high temperatures like other hydrocarbon fuels and produces lesser emissions. Due to the formation of participating gases at high temperature, thermal radiation is generally the dominant mechanism, and, in particular, soot can play an important role in the radiative exchanges even in relatively small concentrations [64-65]. Therefore, an accurate description of gas–soot combined radiation is of great importance in the simulation of combustion.

Inert porous media combustion can only enhance heat recirculation, improve thermal capacity, and intensify gas mixing or diffusion. However, the inert porous media itself cannot promote the fuel combustion or reduce the pollutants emissions. Inert porous media combustion technology has certain limitations regarding fundamentally reducing the fuel activation energy and the flame temperature. Catalytic combustion is a modified technology for lean methane/air premixed combustion that can overcome the above limitations for the inert porous media

combustion. Comprehensive studies have been dedicated to further understanding the catalytic combustion. These studies mainly focused on catalysts, supports, and combustion performances optimizations [66-73].
Although the effect of many parameters on combustion in porous media has been investigated by many investigators, but the influence of fuel injection angle has not been studied. 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.

## 2. COMPUTATIONAL DOMAIN

The three dimensional computations performed in this work have been carried out using the commercial software, FLUENT. The flow is assumed to be steady and laminar. The Navier–Stokes equations and energy equation have been solved, along with the conservation equations for the species participating in the chemical reaction. FLUENT uses a control volume-based technique to convert the governing equations to algebraic equations that can be solved numerically. The second order upwind scheme was used for spatial discretization of all the governing equations. The SIMPLE algorithm is used for pressure and velocity coupling. Pressure interpolation of the pressure values at the faces is done using momentum equation coefficients (standard pressure interpolation scheme). The double-precision segregated solver was utilized for solving the discretized set of algebraic equations.
A common fuel injection valve of a combustion chamber, including a concave conical surface, fuel injection holes at its surface, and a portable needle valve. But here that valve is not modeled through the combustion chamber and just its effect on fuel injection angle is considered. As shown in the Figure 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 combustor is 25 cm in diameter (D) and 100 cm in length (L) that a 1 cm diameter (d) hole at the center is using to deliver the fuel ($CH_4$) with the velocity magnitude of 80 m/s to the burner and the air (0.23 $O_2$ 0.77 $N_2$) is entered from the annular between that hole and burner with the 20 m/s velocity. The fuel injection angle is measured from the axis of symmetric of the combustion chamber. The wall and inlet are held at environment temperature (300 K). Also the computational mesh of the half of the burner with boundary layer mesh t the inlet and the axis of symmetry is illustrated in figure 1. The flames of lean H2 (25%)–CO (25%)–CO2 (50%) mixtures at 1 atm and 303 K were found to exhibit cellular nature. The mixture composition and inlet velocity in the simulations were kept the same as those in the experiments for which photographs were taken.

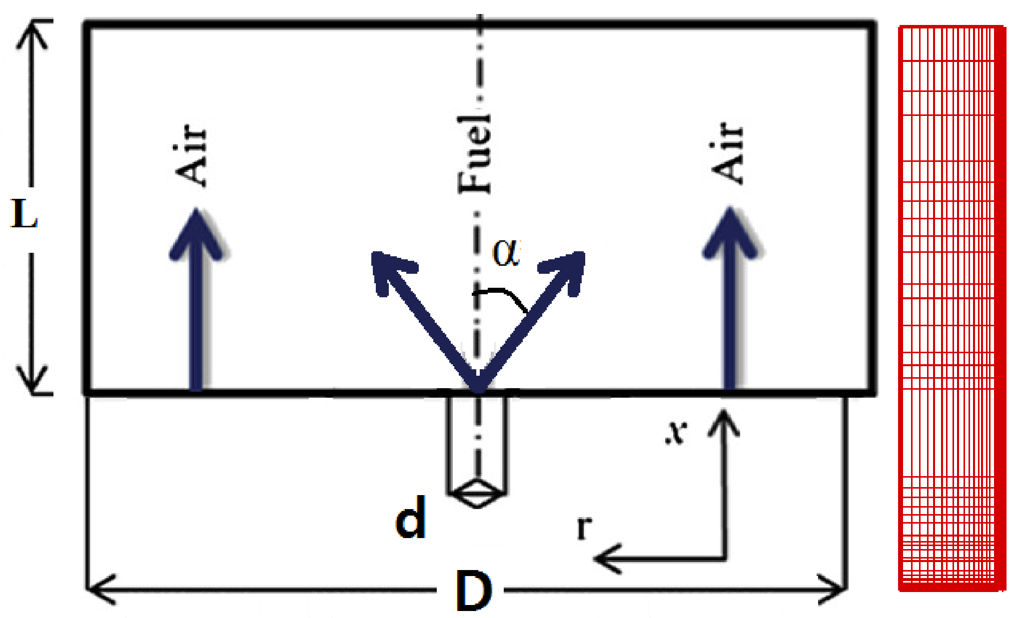


Figure 1: Schematic of the vertical cylinder combustion chamber and the computational mesh

## 3. MATHEMATICAL MODELING

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

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}(rv)=0 \tag{1}$$

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

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

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\rho uh)+\frac{\partial}{\partial x}(r\rho vh)\right]=\Gamma_h\nabla^2 h-\frac{1}{r}\frac{\partial}{\partial r}(r\rho\overline{v'h'})-\frac{\partial}{\partial x}(\rho\overline{u'h'})+\dot{S}_h \tag{4}$$

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\rho u m_j)+\frac{\partial}{\partial r}(r\rho v m_j)\right]=\Gamma_{mj}\nabla^2 m_j-\frac{1}{r}\frac{\partial}{\partial r}(r\rho\overline{v'm_j'})-\frac{\partial}{\partial x}(\rho\overline{u'm_j'})+R_j \tag{5}$$

Where $x$ and $r$ are the axial and radial coordinates [m], $u$ and $v$ are the velocities in these respective directions [m/s], $w$ is the angular velocity [m/s], $\rho$ is the density of the gaseous mixture [kg/m$^3$], $\mu$ is the gaseous mixture dynamic viscosity, and $\mu_t$ is the turbulent viscosity [Ns/m$^2$], defined as $\mu_t = C_\mu \rho k^2/\varepsilon$. The term $p^* = p - (2/3)\ k$ is the modified pressure [Pa], $C_\mu$ is an empirical constant of the turbulence model ($C_\mu = 0.09$), $p$ is the combustion chamber operational pressure ($p = 101325$ Pa), and $k$ [m$^2$/s$^2$] and $\varepsilon$ [m$^2$/s$^3$] are the turbulent kinetic energy and its dissipation. Also, $C_{1,\varepsilon}$ and $C_{2,\varepsilon}$ are empirical constants of the turbulence model ($C_{1,\varepsilon} = 1.44$ and $C_{2,\varepsilon} = 1.92$), $\sigma_k$ and $\sigma_\varepsilon$ are the Prandtl numbers of the kinetic energy and dissipation, respectively ($\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$). $Pr_t$ and $Sc_t$ are the turbulent Prandtl and Schmidt numbers, $R_\alpha$ [kg/(m$^3$ s)] is the volumetric rate of formation or consumption of the$\alpha$th chemical species ($CH_4$, $O_2$, $CO_2$, CO, $H_2O$) . $T$ is the temperature of the gaseous mixture [K], $c_{p,\alpha}$ [kJ/(kg K)], and $T_{ref,\alpha}$ [K] are the molecular mass, the specific heat, the formation enthalpy and the reference temperature of each $\alpha$ th chemical species. $S_{rad}$ [W/m$^3$] is the radiative heat source term, computed as the negative divergence of the radiative heat flux. The turbulent stresses are calculated from an algebraic stress model and wall-function approach is used in the near-wall.

Radiation heat transfer in participating media is governed by the radiative transfer equation (RTE), which establishes a relation for the variation of the spectral radiation intensity $I_\eta$ along a certain path in the medium. The radiative transfer equation (RTE) for non-scattering media, in cylindrical coordinates, with the discrete ordinates method (DOM), subjected to boundary conditions for diffusively emitting and reflecting opaque surface, is used here.

The global solution of the radiative transfer requires the spatial and spectral integrations of Eq. (2-5). In this study, the spatial integration is carried out with the discrete ordinates method to sweep the angular directions, and with the finite-difference method for the discretization of the differential terms in Eq. (2-5). The discrete ordinates solve the RTE for a set of discrete directions that span a total solid angle of $4\pi$. The continuous integral over the solid angle is approximated by a numerical quadrature scheme, in which the equations are solved for a series of L directions.

All the above discussion regarding the solution of the radiative transfer in the medium is applicable to instant quantities that fluctuate in a turbulent flow, while the RANS turbulence model can only provide time-averaged (mean) quantities and, possibly, their mean square fluctuations.

## 4. RESULTS AND DISCUSSION

The conservation equations are solved using the OpenFOAM with the method described in [11]. Figure 2 shows the simulated contours of axial and radial velocities, stream function, water ($H_2O$), carbon dioxide ($CO_2$), and nitrogen ($N_2$) mass concentrations inside the combustor for fuel injection parallel to the axis of burner. As shown the radial velocities are at the one tenth order of the axial velocities, and stream function generally is parallel to the the axis of combustion chamber. The mass concentrations of the oxygen (which is not shown here) is similar to the nitrogen and generally divided to the two regions of inlet and chemical reactions. In order to study the contribution of soot radiation to the radiation heat transfer inside the combustion chamber, two different scenarios were considered. In the first scenario, formation of soot in the chamber was neglected, so only the radiation from the gaseous species was considered. The second scenario considered the formation of soot, taking into account the influence of soot on the radiative heat transfer combined to the gaseous species. Comparisons were made to verify how the different radiative scenarios affected the temperature and radiative heat source fields in the medium, the heat flux distribution

on the chamber wall and the radiant fraction. The most of nitrogen exited from the cavity near the wall and the minimum amount is occurred at the axis of it. The fuel is consumed at the small region near to the inlet and for the products of reaction (water and carbon dioxide) there are three regions in the chamber which are zero at air inlet and 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 cause to create the four regions for the water and carbon dioxide in the chamber which are zero at air inlet and maximum at the middle of the chamber and in moderate concentration in other sides. Because there are not a great change for the pressure inside the chamber that contours are not presented here.
The figure 3 shows that 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. Furthermore it causes the combustion zone of the diffusion flame enlarged and the location of the maximum temperature shifts inside the chamber.
Formation of carbon particles, or soot, is a phenomenon frequently observed in combustion of hydrocarbons, and is recognized as one of the most difficult ongoing research field in combustion. Formation of soot involves chemical and physical processes that are strongly coupled. In terms of fundamental processes, formation of soot consists in three main sub-processes: nucleation of soot particles, coagulation and agglomeration, and surface reactions (growing and oxidation).

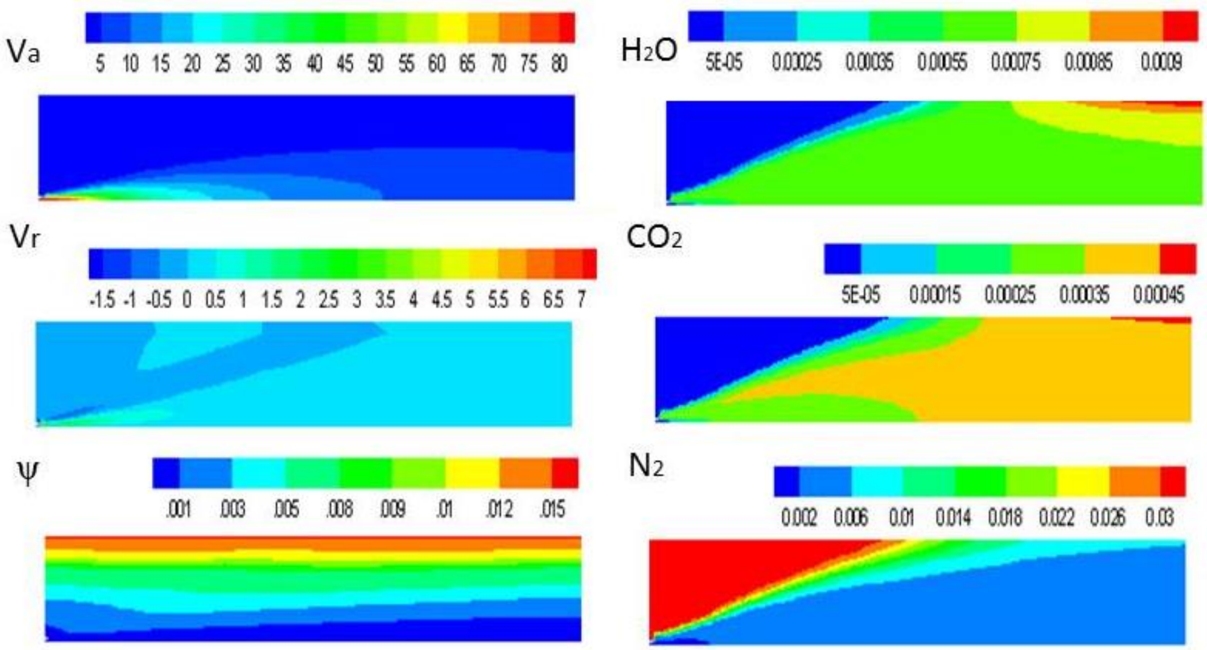


Figure 2: Axial and radial velocites , stream function , $H_2O$, $CO_2$, $N_2$ mass concentrations

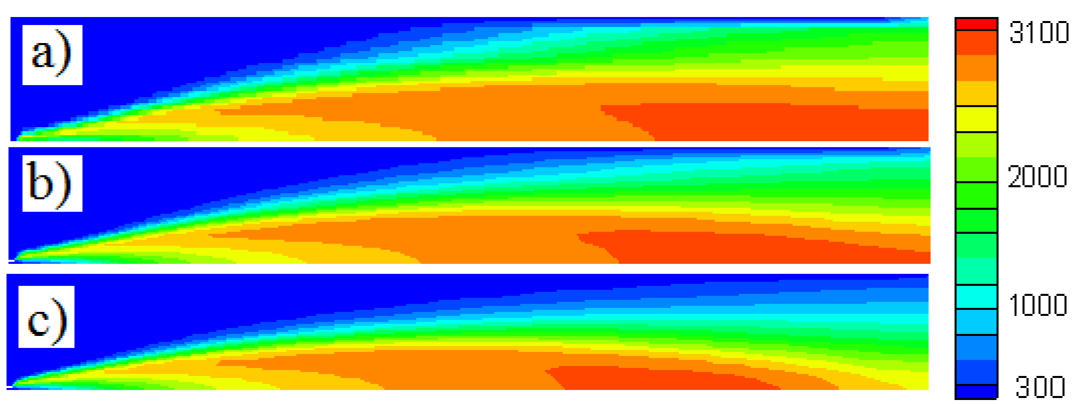


Figure 3: Temperature contours at various fuel injection angle a) α=0 b) α=45º c) α=80º

As expressed before, the obtained temperature distribution of the flame is based on the assumption that the refractive index of the mixture equals to that of the air. Therefore this can be an error source in the experiment. The refractive index value of a mixture is identical to that of the air for partially premixed flames. Specifically the average error caused by this assumption lies in the range of 1.9–2.3% for a 2-D axisymmetric flame for equivalence ratios in the range of $1.5 \leq \Phi \leq 2$s. This error increases by increasing the equivalence ratio of the flame. Therefore the simplified relation obtained for temperature measurement is efficient for relatively fuel-rich partially premixed flames and in this study this constraint was considered for equivalence ratio. The refractive index of air is also dependent on the temperature. Since determination of the air temperature by means of the measured refractive index at high temperatures can be done by the Gladstone–Dale constant and the variation of air refractive index is negligible for temperatures up to 6000 K and pressure changes from 0.1 to 10 atm. It was explained by the lack of notable dissociation of nitrogen molecules as nitrogen dissociation develops in 6000–8000 K temperature range. Another source of error is the deflection of the laser beam. When the laser beam passes through the test section it is slightly deflected within the flame therefore it does not travel along its original path when reflected by mirror. This divergent angle has no significant impact in Mach–Zehnder interferometer. Another source of error in combustion experiments is due to equivalence ratio. The maximum uncertainty for the equivalence ratio is ±2.3% at $\Phi$=2.1 for the methane/air mixture.

## 6. CONCLUSIONS

This study presented an analysis of the effect of soot on the radiative heat transfer in a turbulent non-premixed methane–air flame in a cylindrical combustion chamber. The radiation field was computed with the RTE model using recently obtained correlations based on the up-to-date for the gaseous mixture and soot. Burning behaviors of non-premixed methane-air flame are studied for different fuel injection angles. As shown the fuel injection angle is an efficient parameter to control the fluid flow and combustion characteristics through the combustion chamber. With the increase in $H_2$ content in mixture of $H_2$–CO with fixed $CO_2$ dilution burning velocity increases significantly. This is mainly due to the high reactivity of $H_2$ leading to high heat release rates and this can be clearly observed as the reaction of rates of $H + O_2 \rightleftarrows O + OH$ and $OH + H_2 \rightleftarrows H + H_2O$ are three times for 4:1 $H_2$:CO ratio in comparison to those for 1:4 with 50% $CO_2$ dilution.

From simulations of cellular flames, volumetric heat release rates were plotted at various horizontal planes parallel to the burner surface. Such plots helped identify the cells in the simulation. The cell count and cell sizes in simulations agreed very well with observations in corresponding experiments.

## REFERENCES

[1] S. R. Turns, An Introduction to Combustion: Concepts And Application, McGraw-Hill Science, (2006).

[2] J. Warnatz, U. Mass and R. W. Dibble, 2006. Combustion, Physical and Chemical Fundamentals, Modeling and Simulation, Experiments, Pollutant Formation. Springer.

[3] Fand, R.M., Kim, B.Y.K., Lam, A.C.C., Phan, R.T., "Resistance to the Flow of Fluids through Simple and Complex Porous Media whose Matrices are Composed of Randomly Packed Spheres", Journal of Fluid Engineering, Transaction of ASME, Vol.109,1987, pp. 268-274.

[4] Hall, M.J., Hiatt, J.P., "Exit Flows from Highly Porous Media", Physics of Fluids, Vol. 6, 1994, pp. 469-479.

[5] Horton, N.A., Pokrajac, D., "Onset of Turbulence in a Regular Porous Medium: An Experimental Study", Physics of Fluids, Vol. 21, 2009, article No.045104.

[6] Lage, J.L., "The Fundamental Theory of Flow through Permeable Media from Darcy to Turbulence", Transport Phenomena in Porous Media, Ingham, D.B., Pop, I., (Eds.), Pergamon,1998, pp. 11-30.

[7] Hsu, F.P., Evans, D.W., Howell, R.J., "Experimental and Numerical Study of Premixed Combustion within Non-homogeneous Porous Ceramics", Combustion Science and Technology, Vol. 90, 1993, pp. 149-172.

[8] Malico, I., Zhou, X.Y., Pereira, J.C.F., "Two dimensional Numerical Study of Combustion and Pollutants Formation in Porous Burners", Combustion Science and Technology, Vol. 152,2000, pp. 57-72.

[9] Hackert, L.C., Ellzey, L.J., Ezekoye, A.O., "Combustion and Heat Transfer in Model Two dimensional Porous Burners", Combustion and Flame, Vol. 116, 1999, pp. 177-191.

[10] Howell, J.R., Hall, M.J., Ellzey, J.L., "Combustion of Hydrocarbon Fuels within Porous Inert Media", Progress in Energy and Combustion Science, Vol.22, 1996, pp. 121-145.

[11] Kamal, M.M., Mohamad, A.A., "Combustion in Porous Media", Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 220, 2006, pp. 487-508.

[12] Antohe, B.A., Lage, J.L., "A General Two-equation Macroscopic Model for Incompressible Flow in Porous Media", International Journal of Heat and Mass Transfer, Vol. 40, 1997, pp. 3013-3024.

[13] Nakayama, A., Kuwahara, F., “A Macroscopic Turbulence Model for Flow in a Porous Medium”,Journal of Fluids Engineering, Vol. 121, 1999, pp.427-433.
[14] Pedras, M.H.J., de Lemos, M.J.S., “Macroscopic Turbulence Modeling for Incompressible Flow through Undeformable Porous Media”, International Journal of Heat and Mass Transfer,Vol. 44, 2001, pp. 1081-1093.
[15] Teruel, F.E., Rizwan-uddin, “A New Turbulence Model for Porous Media Flow, Part I: Constitutive Equation and Model Closure”, International Journal of Heat and Mass Transfer, Vol. 52, 2009,pp. 4264-4272.
[16] Nimvari, M.E., Maerefat, M., El-Hossaini, M.K., “Numerical Simulation of Turbulent Flow and Heat Transfer in a Channel Partially Filled with a Porous Media”, International Journal of Thermal Sciences, Vol. 60, 2012, pp. 131-141.
[17] De Lemos, M.J.S., “Numerical Simulation of Turbulent Combustion in Porous Materials”, International Communications in Heat and Mass Transfer, Vol. 36, 2009, pp. 996-1001.
[18] Barra, A.J., Diepvens, G., Ellzey, J.L., Henneke, M.R., “Numerical Study of the Effects of Material Properties on Flame Stabilization in a Porous Burner”, Combustion and Flame, Vol. 134, 2003, pp. 369-379.
[19] Chaffin, C., Koening, M., Koeroghlian, M., Matthews, R., Hall, M., Nichols, S., Lim, I., “Experimental Investigation of Premixed Combustion within Highly Porous Media”, Proceeding of the ASME/JSME Thermal Engineering Joint Conference, Vol. 4, 1991, p. 219.
[20] Kee, R.J., Rupley, F.M., Miller, J.A., “CHEMKINII: A FORTRAN Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics”,Report No. SAND89-8009B, Sandia National Laboratories, 1993.
[21] De Lemos, M.J.S., Turbulence in Porous Media: Modeling and Applications, First Ed., Kidlington, Elsevier, 2006.
[22] Younis, L.B., Viskanta, R., “Experimental Determination of the Volumetric Heat Transfer Coefficient between Stream of Air and Ceramic Foam”, International Journal of Heat and Mass Transfer, Vol. 36, 1993, pp. 1425-1434.
[23] Jones, W.P., Launder, B.E., “The Prediction of Laminarization with Two-equation Model of Turbulence”, International Journal of Heat and Mass Transfer, Vol. 15, 1972, pp. 301-314.
[24] De Lemos, M.J.S., Pevim, A.C., “Turbulent Flow with Combustion in a Moving Bed”, International Communications in Heat and Mass Transfer, Vol. 39, 2012, pp. 1-7.
[25] Diamantis, D.J., Mastorakos, E., Goussis, D.A., “Simulations of Premixed Combustion in Porous Media”, Combustion Theory and. Modeling, Vol. 6, 2002, pp. 383-411.
[26] Wharton, J.A., Ellzey, J.L., Bogard, D.G., “An Experimental Study of Turbulence Intensities and Non-uniformities in the Exit Flow from a Porous Medium”, Experimental in Fluids, Vol. 38, 2005,pp. 701-707.
[27] Tseng, C., “Effects of Hydrogen Addition on Methane Combustion in a PorousMedium Burner”, International Journal of Hydrogen Energy, Vol. 27, 2002, pp. 699-707.
[28] Blint, R.J., “The Relationship of the Laminar Flame Width to Flame Speed”, Combustion Science and Technology, Vol. 49, 1986,pp. 79-92.
[29] Mathis, W.M., Ellzey, J.L., “Flame Stabilization, Operating Range, and Emissions for a Methane/Air Porous Burner”, Combustion Science and Technology, Vol. 175, 2003, pp. 825-839.
[30] Brenner, G., Pickenacker, K., Pickenacker, O., Trimis, D., Wawrzinek, K., Weber, T., “Numerical and Experimental Investigation of Matrix-Stabilized Methane/Air Combustion in Porous Inert Media”, Combustion and Flame, Vol. 123, 2000,pp. 201-213.
[31] Williams, A., Woolley, R., Lawes, M.F., “Formation of NOx in Surface Burner”, Combustion and Flame, Vol. 89 1992, pp. 157-166.
[32] Afsharvahid, S., Ashman, P.J., Dally, B.B., “Investigation of NO Conversion Characteristics in a Porous Medium”, Combustion and Flame, Vol.152, 2008, pp. 604-615.
[33] Hassan I. Kassem, Khalid M. Saqr, Hossam. S. Aly, Mohsin M. Sies, Mazlan Abdul Wahid, Implementation of the eddy dissipation model of turbulent non-premixed combustion in OpenFOAM ,International Communications in Heat and Mass Transfer,38,363–367 (2011).
[34] Modest, M.F., Radiative Heat Transfer, Second Ed., New Jersey, McGraw-Hill, 2003.
[35] M.Y. Abdollahzadeh Jamalabadi, Effects of micro and macro scale Viscous Dissipations with Heat Generation and Local Thermal Non-Equilibrium on Thermal Developing Forced Convection in saturated porous media, Journal of Porous Media , (18) 9 (2015) 843-860
[36] M.Y. Abdollahzadeh Jamalabadi, Joule Heating in Low-Voltage Electroosmotic with Electrolyte containing nano-bubble mixtures through Microchannel Rectangular Orifice, Chemical Engineering Research and Design, 102 (2015) 407-415

[37] M.Y. Abdollahzadeh Jamalabadi, M.Ghasemi,M.H.Hamedi, Two-dimensional simulation of thermal loading with horizontal heat sources, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 226 (2012) 1302-1308

[38] A.Shahidian, M.Ghassemi, S.Khorasanizade, M.Abdollahzade, G.Ahmadi, Flow Analysis of Non-Newtonian Blood in a Magnetohydrodynamic Pump, IEEE Transactions on Magnetics (45) 6 (2009) 2667-2670

[39] M.Y. Abdollahzadeh Jamalabadi, J.H.Park, M.M. Rashidi ,J.M. Chen, Effects of Thermal Boundary Conditions on the Joule Heating of Electrolyte in a Microchannel, Journal of Hydrodynamics, Ser. B, accepted for publication (2015)

[40] M. S. Shadloo,R. Poultangari, M.Y. Abdollahzadeh Jamalabadi, M.M. Rashidi ,A New and Efficient Mechanism for Spark Ignition Engines, Energy Conversion and Management, 96 (2015) 418-429

[41] M.Y. Abdollahzadeh Jamalabadi, J.H.Park,C.Y. Lee, Optimal Design of MHD Mixed Convection Flow in a Vertical Channel with Slip Boundary Conditions and Thermal Radiation Effects by using Entropy Generation Minimization Method, entropy, (2015) 17 (2), 866-881

[42] M.Y. Abdollahzadeh Jamalabadi and J.H.Park, Effects of Brownian motion on Freezing of PCM Containing Nanoparticles, Thermal Science, OnLine-First Issue 00 (2014) 94-94

[43] M.Y. Abdollahzadeh Jamalabadi,J.H.Park, C.Y. Lee,Thermal Radiation effects on the Onset of Unsteadiness of Fluid Flow in Vertical Microchannel Filled with Highly Absorbing Medium, Thermal Science, OnLine-First Issue 00 (2014) 124-124

[44] M.Y. Abdollahzadeh Jamalabadi, M.Ghasemi,M.H.Hamedi ,Numerical Investigation of Thermal Radiation Effects on Open Cavity with Discrete Heat Sources, International Journal of Numerical Methods for Heat and Fluid Flow (23) 4 (2013) 649-661

[45] M.Y. Abdollahzadeh Jamalabadi, Electrochemical and exergetic modeling of a CHP system using tubular solid oxide fuel cell and mini gas turbine , J. Fuel Cell Sci. Technol 10(5) 051007 (2013) FC-13-1039

[46] M.Y. Abdollahzadeh Jamalabadi, Optimal Design of Cylindrical PBX by Entransy Dissipation Extremum Principle, International Journal of Energetic Materials and Chemical Propulsion, accepted for publication, 15 (2016)

[47] M.Y. Abdollahzadeh Jamalabadi, Thermal Radiation Effects on Creep Behavior of the Turbine Blade , Multidiscipline Modeling in Materials and Structures, minor revision (2016)

[48] S.Bita, M.Y. Abdollahzadeh Jamalabadi,M. Mesbah,Toxicity study of silver nanoparticles synthesized using seaweed Sargassum angustifolium in common carp, Cyprinus carpio, Journal of Chemical and Pharmaceutical Research, accepted for publication (2015)

[49] M.Y. Abdollahzadeh Jamalabadi,Entropy generation in boundary layer flow of a micro polar fluid over a stretching sheet embedded in a highly absorbing medium, Frontiers in Heat and Mass Transfer ,6 (1) (2015) 1-13

[50] M.Y. Abdollahzadeh Jamalabadi, The frequency response of a cavitating hydrofoil, Noise and Vibration Worldwide (45) 8 (2014) 21-27

[51] M.Y. Abdollahzadeh Jamalabadi,Analytical study of Magnetohydrodynamic propulsion stability, Journal of Marine Science and Application (13) 3 (2014) 281-290

[52] M.Y. Abdollahzadeh Jamalabadi, Experimental investigation of thermal loading of a horizontal thin plate using infrared camera, Journal of King Saud University – Engineering Sciences (26) 2 (2014) 159-167

[53] M.Y. Abdollahzadeh Jamalabadi, J.H.Park,C.Y. Lee, Economic and environmental modeling of a micro gas turbine and solid oxide fuel cell hybrid combined heat and power system, International Journal of Applied Environmental Sciences, (9) 4 (2014) 1769-1781

[54] M.Y. Abdollahzadeh Jamalabadi, Simulation of electrochemical impedance spectroscopy of a solid oxide fuel cell anodes, World Applied Sciences Journal(32) 4 (2014) 667-671

[55] M.Y. Abdollahzadeh Jamalabadi and J.H.Park, Investigation of property variations on freezing of pcm containing nanoparticles, World Applied Sciences Journal(32) 4 (2014) 672-677

[56] M.Y. Abdollahzadeh Jamalabadi, Economic and environmental modeling of a MGT-SOFC hybrid combined heat and power system for ship applications, Middle-East Journal of Scientific Research 22 (4)( 2014) 561-574

[57] M.Y. Abdollahzadeh Jamalabadi, MD simulation of Brownian motion on trapping of Buckminsterfullerene in nano-Optical tweezers, International Journal of Optics and Applications, (5) 5 (2015) 161-167

[58] M.Y. Abdollahzadeh Jamalabadi, Numerical investigation of thermal radiation effects on electrochemical impedance spectroscopy of a solid oxide fuel cell anodes, Materials Performance and Characterization, DOI: 10.1520/MPC20140062 (2015)

[59] M.Y. Abdollahzadeh Jamalabadi, 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, International Journal of Energy Engineering, 5,1 (2015) 1-8
[60] M.Y. Abdollahzadeh Jamalabadi and J.H. Park, Thermal radiation, joule heating, and viscous dissipation effects on mhd forced convection flow with uniform surface temperature, Open Journal of Fluid Dynamics (4) 2 , (2014) 125-132
[61] M.Y. Abdollahzadeh Jamalabadi, Effect of fuel inject angle on non-premixed combustion of air/methane mixtures in vertical cylinder, International Journal of Multidisciplinary Research and Development, (1) 5 (2014) 1-4
[62] M.Y. Abdollahzadeh Jamalabadi and J.H.Park, Electro-Magnetic Ship Propulsion Stability under Gusts, International Journal of Sciences: Basic and Applied Research Sciences 1 (2014) 421-427
[63] M.Y. Abdollahzadeh Jamalabadi, P. Hooshmand, B. Khezri, A. Radmanesh, Investigation of using different fluids for using in gas turbine- Rankine cycle, Indian journal of Scientific Research (2) (2014) 74-81
[64] S. Dousti, J. Cao, A. Younan, P. Allaire, T. Dimond, "Temporal and Convective Inertia Effects in Plain Journal Bearings With Eccentricity, Velocity and Acceleration", Journal of tribology 134 (3), 031704,8,2012.
[65] S. Dousti, J.A. Kaplan, F. He, P.E. Allaire, “Elastomer O-Rings as Centering Spring in Squeeze Film Dampers: Application to Turbochargers”, ASME Turbo Expo 2013: Turbine Technical Conference and Exposition,2,2013.
[66] F. He, P.E. Allaire, S. Dousti, A. Untaroiu, “Forced response of a flexible rotor with squeeze film damper under parametric change”, ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, 1, 2013.
[67] S. Dousti, R.L. Fittro, “An Extended Reynolds Equation Including the Lubricant Inertia Effects: Application to Finite Length Water Lubricated Bearings”, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, 2015.
[68] E. Sarshari, N. Vasegh, M. Khaghani, S. Dousti, “Sliding Mode Control in Ziegler’s Pendulum With Tracking Force: Novel Modeling Considerations”, ASME 2013 International Mechanical Engineering Congress and Exposition, 2013.
[69] S. Dousti, T.W. Dimond, P.E. Allaire, H.E. Wood, “Time Transient Analysis of Horizontal Rigid Rotor Supported With O-Ring Sealed Squeeze Film Damper”, ASME 2013 International Mechanical Engineering Congress and Exposition, 2013.
[70] S. Dousti, M.A. Jalali, “In-Plane and Transverse Eigenmodes of High-Speed Rotating Composite Disks”, Journal of Applied Mechanics, 80 (1), 011019, 2013.
[71] Jafarzadeh, H., Gholami, S. & Bashirzadeh, R. (2014). A new effective algorithm for on-line robot motion planning.Decision Science Letters , 3(1), 121-130.
[72] Hasani, R., Jafarzadeh, H. & Khoshalhan, F. (2013). A new method for supply chain coordination with credit option contract and customers’ backordered demand.Uncertain Supply Chain Management, 1(4), 207-218.
[73] Hassanzadeh, A., Mohseninezhad, L., Tirdad, A., Dadgostari, F., & Zolfagharinia, H. (2009). Location-routing problem. In Facility Location (pp. 395-417). Physica-Verlag HD.