Numerical Simulation of Hydrogen Fueled Porous Burner*

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Abstract

Porous media burners in comparison with free flame burners have major benefits such as higher thermal efficiency, stable flame in a wider range of stoichiometric ratios and feed flow rates, capability of using low calorific fuels and low production of pollutants. In the present study, premixed and laminar combustion of hydrogen in a solid matrix with spongy lattice is simulated. The axisymmetric solid matrix is considered to be inert, isotropic and homogenous in the unsteady simulations. The burner consists of a divergent inlet followed by a constant area section. A multi-step chemical kinetics is implemented. Heat exchange between the solid and gas phases is simulated using an experimental correlation for volumetric convective heat transfer coefficient, and the diffusion approximation is used to simulate the radiation mechanism inside the solid matrix. All physical properties of the gas mixture are considered as functions of local temperature and mixture composition. The governing equations are discreted and solved by the control volume scheme and SIMPLE algorithm. The effects of certain parameters such as flow rate and physical properties of the solid matrix on the thermal/stability performance of the burner are analyzed. Increasing the feed flow rate causes upstream movement of the flame front and increase in the flame temperature and pollutant formation. The flammability limits are obtained in the range of stoichiometric ratios between 0.5 and 1.2, where the widest belongs to a stoichiometric mixture.

Key words: Porous Burner, Thermal Characteristics, Matrix Structural Properties, Reactants Properties, Preheating Zone Efficiency

1. Introduction

Combustion has been one of the major sources of achieving required energy for mankind during the history. To obtain an efficient and reliable combustion, burner technology is developed and modern burners are introduced each day. Combustion in porous burner is one of these technologies which proved to be obliging.

The enhanced characteristics of combustion in porous media are due to high heat
recirculation by two mechanisms of solid conduction and solid-to-solid radiation from the flame downstream to its upstream in the matrix. Convective heat transfer between the solid and gas phase causes an effective preheating of the reactants, which results in a considerable increase in the flame speed and temperature.

As the fossil fuel supplies are lowering and the environmental pollution becoming a universal crisis, replacement of common fuels with an available and clean fuel, like hydrogen attracts a lot of interest.

Enhanced efficiencies, higher power densities, higher dynamic power ranges, high compactness and controlled pollutant emissions are some of porous burners characteristics, which have made them different from conventional free-flame burners [1,2].

The high temperature post flame zone serves to heat the porous solid in the preheating zone with radiation and conduction heat transfer mechanisms through the solid medium, which in turn convectively preheats the incoming reactants. This regenerative internal heat feedback mechanism results in several interesting characteristics relative to a free burning flame, namely higher burning speeds, extension of the lean flammability limit and ability to burn fuels with low energy content.

The inception point in the study of porous burners may date back to the early eighties. In 1971, Weinberg [3] proposed several heat recirculating burners, where the flue gases were partially used in the preheating of the reactants by using a heat exchanger. Inserting a porous highly conductive matrix into the flame location to make a more effective transfer of heat from the solid to the reactants was first suggested by Takeno and Sato [4]. Another early analysis was performed by Echigo [5] to investigate the ability of converting some of the enthalpy of a non-reacting hot gas to increase the temperature of porous medium through radiative heat transfer mechanism. Since then, especially over the last two decades, considerable efforts have been made in the development and applications of porous media combustion and heat recirculation technology [6,7].

The solid region of a porous burner can be divided into two zones: the preheating and reaction zones. In the preheating zone the solid phase temperature exceeds the gas temperature, while in the reaction zone the combustion reactions causes a considerable increase in the gas phase temperature. In comparison to a premixed laminar free flame, the preheating zone in a porous burner is much more effective. The thermal performance and pollutant formation in a porous burner are compellingly affected by the length of the matrix preheating zone and the capability of this region in heat recirculation through the solid phase. An efficient preheating zone causes an effective heat transfer between the two phases and increases the reactants temperature entering the reaction zone considerably, which in turn affects the formation of pollutants.

In an analytical work using a prescribed flame location Yoshizawa et al. [8] showed that temperature profiles and burning velocities are highly dependent on the optical and structural properties of the porous matrix. Excess enthalpy flames were predicted due to the presence of the solid phase. According to their modeling, the single most important solid property governing the flame behavior is the absorption coefficient.

A numerical investigation of premixed combustion within a highly porous inert medium was reported by Hsu et al. [9]. The simulated burner was an 8-cm long partially stabilized zirconia cylinder. An improved description of the thermophysical properties of the solid was used in the modeling; however, the flame location was arbitrarily prescribed. It was found that the preheating effect is increased strongly with increasing convective heat transfer and effective thermal conductivity of the solid. The volumetric convective heat transfer was expected to increase with increasing the number of cells per unit length of the porous matrix, but the absorption coefficient decreased with increasing cell size and decreasing cell density.

Mohamad et al. [10] numerically studied combustion and heat transfer in a porous
matrix burner consisting of a packed bed of ceramic particles with two rows of embedded cooling tubes. They used a two-dimensional model, single-step kinetics, and a single energy equation for the solid and gas phases by assuming that the gas and the solid matrix are in thermal equilibrium. The predicted results showed that the flame location is a strong function of the excess air and is also sensitive to the uncertainty in the activation energy.

A one-dimensional theoretical study of the heating effectiveness of a composite porous radiant burner (PRB) was conducted by Kulkarni and Peck [11]. A parametric study was carried out to determine the effect of the radiative and structural properties of the two porous layers on the burner performance. Calculations indicated that a significant improvement in the radiative output of a PRB can be attained by optimizing the burner properties upstream and downstream of the flame.

Mital [12] proposed both experimental and theoretical models for combustion and heat transfer in a two-stage porous burner to study the thermal characteristics of reticulated ceramics. His burner was composed of a diffuser layer (DL) and a flame support layer (FSL). The DL was made from cordierite with a porosity of 0.73 and 19 mm thickness. The FSL was 2-mm thick with a porosity of 0.83. It was observed that the flame was stabilized in the middle of the FSL. Fu [13] attempted to improve the approximate analytical model proposed by Mital. In a comprehensive parametric study, he showed that temperatures of both the solid and the gas in the flame support layer increased with an increase in the firing rate, due to amplifying of chemical heat release rate and the convective heat transfer rate with firing rate.

Barra and Ellzey [14] analyzed heat recirculation in a two-layered porous burner using a one-dimensional model. It was concluded that the burner length does not significantly affect the amount of the recirculated heat. In addition, the relative importance of conduction and radiation heat transfer mechanisms is unchanged. They suggested a bi-layer solid structure to improve the flash-back resistance of the burner.

In 2009, Krittacom and Kamiuto [15], examined both numerically and experimentally performance of a premixed methane-air, open-cellular porous burner. Both P1 approximation and Barkstrom’s method are utilized to investigate the radiation characteristics of the burner. Acceptable agreement between numerical (with both radiation models) and experimental data accompanied by specification of burner stable operating condition are the main achievements.

In the present study, the effects of feed gas velocity (firing rate) and mixture stoichiometric ratio on the overall thermal performance and stability of a premixed hydrogen/air porous burner is numerically investigated. An axisymmetric, laminar and unsteady flow model for an adiabatic, inert, isotropic and homogeneous ceramic foam burner is used.

To simulate the combustion process, a published summarization of a detailed hydrogen/air mechanism to some basic elementary reactions is utilized to capture the production rate behavior of NO species. In this study, the flame location is not predetermined, and the thermo-physical properties of the gas mixture are taken as functions of temperature. Extension of the computational domain beyond either side of the porous region results in an accurate modeling of the reactions close to the edges of the porous region, and allows prediction of flash-back and blow-out phenomena. Performance-stability diagram of the analyzed burner is produced by considering 60 different scenarios at which stable flame occurs inside the solid matrix.

Nomenclature

\[
\begin{align*}
A & \quad \text{pre-exponential factor} \left( \frac{m^3}{kg \cdot s} \right) \\
C & \quad \text{specific heat} \left( \frac{kJ}{kg \cdot K} \right)
\end{align*}
\]
2. Numerical model

2.1. Model specifications

An axisymmetric, laminar and unsteady flow model for an adiabatic, inert, isotropic and homogeneous ceramic foam burner is used.

The schematic of the studied porous burner accompanied with some boundary conditions and geometrical dimensions is shown in Fig.1. The porous zone is identified by...
the hatched middle section and two upstream and downstream sections are considered to capture the flash back and blow out behaviors of the flame.

![Adiabatic walls](image)

Fig. 1: Schematic of the utilized burner geometry with some boundary conditions.

The ceramic foam substance is assumed to be SiC with the physical properties presented in Table 1. The boundary conditions for the base case are listed in Table 2.

Table 1: Physical properties of the presented porous burner.

<table>
<thead>
<tr>
<th>Material</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.81</td>
</tr>
<tr>
<td>Hydraulic diameter</td>
<td>0.83×10⁻³ m</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>800 J/kg-K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>35 W/m-K</td>
</tr>
<tr>
<td>density</td>
<td>810 kg/m³</td>
</tr>
<tr>
<td>Emissivity coefficient</td>
<td>0.9</td>
</tr>
<tr>
<td>Extinguish coefficient</td>
<td>500 m⁻¹</td>
</tr>
</tbody>
</table>

\[
Nu = 0.95Re^{0.35}Pr^{1.0}
\]

Table 2: Boundary conditions for the base case.

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed velocity</td>
<td>1.5 m/s</td>
</tr>
<tr>
<td>Feed temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>Feed stoichiometric ratio</td>
<td>1.0</td>
</tr>
<tr>
<td>Inlet cone inclination</td>
<td>45 °</td>
</tr>
</tbody>
</table>

The spark mechanism for initiating the combustion process is simulated by increasing the temperature of a narrow section in the middle of porous zone artificially. After initiation of combustion reactions the artificial temperature increase is removed exponentially through time.

2.2. Governing equations

The model utilizes a spatial averaged approach to derive the conservation equations in the porous solid, and does not assume thermal equilibrium between the solid and gas. It takes into account the effects of solid and gas conduction, solid-to-solid radiation, convective heat
transfer between the solid and the gas and species diffusion. For further details of the model specifications, one is referred to [16].

The following equations are solved simultaneously to simulate the thermo-fluid characteristics of hydrogen porous burner.

Continuity equation:

\[ \frac{\partial (\rho_g \phi_g)}{\partial t} + \nabla \cdot (\rho_g \phi_g \mathbf{V}) = 0 \]  (1)

where \( \mathbf{V} \) denotes the fluid Darcy velocity.

Momentum equation:

\[ \phi_g \frac{\partial \mathbf{V}}{\partial t} + \rho_g \phi_g \mathbf{V} \nabla \mathbf{V} = -\phi \mathbf{V} \mathbf{p} + \rho_g \phi_g \mathbf{V} \nabla (\nabla \mathbf{V}) - (\nabla \mathbf{V}) \mathbf{p} \]  (2)

where \( \phi \) stands for the porosity. The modeling of pressure drop inside the porous zone is achieved by the \( (\nabla \mathbf{V}) \mathbf{p} \) term on the right side of equation (2) and is calculated using the modified Ergun equation as:

\[ (\nabla \mathbf{V}) \mathbf{p} = \frac{180(1-\phi)^2 \mu_g \phi_g \mathbf{V} + 1.8(1-\phi)\mu \mathbf{V}}{\phi^3 d_b^2} \]  (3)

Gas phase energy equation:

\[ \rho_g c_p g \phi_g \frac{\partial T_g}{\partial t} + \rho_g c_p g \phi g \mathbf{V} \nabla T_g = \phi N \{ \lambda_g \mathbf{V} \nabla T_g \} - \phi \sum_{i=1}^{N} h_i \omega_i + H_v \{ T_s - T_g \} \]  (4)

where \( h_i \) and \( \omega_i \) are enthalpy and production rate of the \( i^{th} \) species in \( J/kg \) and \( kg/m^3-s \), respectively. The 2nd and 3rd terms on the right side of equation (4) denote the generated chemical energy and heat transfer between fluid and solid phases of the porous zone.

The solid phase radiation mechanism is modeled through the effective conduction coefficient. As the dimension optical thickness of the porous medium is defined by:

\[ \tau = \beta L \]  (8)

is vividly larger than unity, the diffusion approximation for radiation modeling is valid. Therefore the following equivalent conduction coefficient could be used:

\[ \lambda_{s, rad} = \frac{16n^2 \sigma T_s^3}{3\beta(1-\phi)} \]  (9)

The constant parameters in the above equation are listed in Table 1. Therefore, according to the diffusion approximation, the effective conduction coefficient is defined as:

\[ \lambda_{s, eff} = \lambda_{s, cond} + \lambda_{s, rad} \]  (10)

This equation states that the effective thermal conductivity of the solid phase is the sum of the conductivities due to conduction and radiation as suggested by [16].

Conservation of chimerical species:


\[
\phi \frac{\partial Y_i}{\partial t} + \rho \nabla \cdot (D_{im} \nabla Y_i) = \phi \rho \nabla \cdot (D_{im} \nabla Y_i) + \phi \omega_i
\]  

(11)

\[D_{im} \text{ is the effective binary diffusion coefficient and is calculated using:}
\]

\[
D_{im} = \frac{1 - \chi_i}{\sum_{j=1}^{N} \chi_i D_{ij}}
\]  

(12)

where \( \chi_i \) and \( D_{ij} \) are mole fraction and binary diffusion coefficient, respectively.

2.3. Chemical kinetics

It is evident that global chemical reaction rate constants which are usually obtained under adiabatic free combustion conditions are not applicable to non-adiabatic combustion occurring within porous media. It is also important to note that, in general, even a global chemical mechanism correlated for combustion in a specific porous medium is not applicable for another one.

Several global and detailed kinetic models are presented for reaction rate of hydrogen/air mixture combustion. One of the most cited studies in this field is performed by Konnov et al. (2001) [17]. A detailed hydrogen/air mechanism is provided and summarized to some basic elementary reactions to capture the production rate behavior of NO species. These basic elementary reactions are listed in Table 3.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( A \text{ cm}^3\text{mol}^{-m-1}\text{s}^n )</th>
<th>( n )</th>
<th>( \text{Ea} \text{ (cal/mol)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 O+H(_2)=OH+H</td>
<td>5.06\times10^{14}</td>
<td>2.67</td>
<td>6285</td>
</tr>
<tr>
<td>2 H+O(_2)=OH+O</td>
<td>1.00\times10^{14}</td>
<td>0</td>
<td>14843</td>
</tr>
<tr>
<td>3 H(_2)+OH=H(_2)O+H</td>
<td>1.00\times10^{14}</td>
<td>1.6</td>
<td>3300</td>
</tr>
<tr>
<td>4 N(_2)+O=NO+N</td>
<td>1.80\times10^{14}</td>
<td>0</td>
<td>76100</td>
</tr>
<tr>
<td>5 N(_2)O(\text{(+M)})=N(_2)O(\text{(+M)})</td>
<td>4.0\times10^{14}</td>
<td>0</td>
<td>56640</td>
</tr>
<tr>
<td>6 N(_2)O+O=N(_2)+O(_2)</td>
<td>1.00\times10^{14}</td>
<td>0</td>
<td>28200</td>
</tr>
<tr>
<td>7 N(_2)O+O=NO+NO</td>
<td>6.92\times10^{14}</td>
<td>0</td>
<td>26630</td>
</tr>
<tr>
<td>8 NNH=N(_2)+H</td>
<td>3.00\times10^{14}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9 N(_2)O+H=N(_2)+OH</td>
<td>2.20\times10^{14}</td>
<td>0</td>
<td>16750</td>
</tr>
<tr>
<td>10 N(_2)O+H=NH+NO</td>
<td>6.70\times10^{22}</td>
<td>-2.16</td>
<td>37155</td>
</tr>
<tr>
<td>11 NH+NO=NNH+O</td>
<td>5.60\times10^{12}</td>
<td>0.21</td>
<td>10870</td>
</tr>
</tbody>
</table>

\(^m\) is the reaction order

Basic NO production mechanism (e.g. Extended Zeldovich, N\(_2\)O mechanism and NNH mechanism) are considered and the following relations for N\(_2\)O production are presented:

Zeldovich mechanism:

\[
\frac{d[\text{NO}]}{dt} = 2k_{21}K_2K_3[H_2][O_2][N_2]/[H_2O]
\]  

(13)

NO production through NNH mechanism

\[
\frac{d[\text{NO}]}{dt} = 2k_{21}K_{k_8}K_2^{1/2}K_2^{1/2}[N_2][H_2][O_2]^{3/2}/[H_2O]^{1/2}
\]  

(14)

NO production through N\(_2\)O mechanism

\[
\frac{d[\text{NO}]}{dt} = (2k_7K_2^{1/2}[O_2]^{1/2} + 2k_{10}K_1^{1/2}[H_2]^{1/2}) \times \frac{k_{k_8}K_2K_3[H_2][N_2][O_2][M]}{((k_6 + k_7)K_2^{1/2}[O_2]^{1/2} + (k_8 + k_{10})K_1^{1/2}[H_2]^{1/2})[H_2O]^{1/2}}
\]  

(15)

In the above reaction rate equations [ ] symbol denotes the chemical concentration and \( k_i \) and \( K_i \) (equilibrium constant) are calculated using:
\[ k_i = AT^n \exp\left(-\frac{E_{a,i}}{RT}\right) \] (16)

\[ K_i = \exp\left[-\frac{\Delta G_{T,i}^0}{R_uT_g}\right] \] (17)

where \( \Delta G_{T,i}^0 \) stands for the change of standard-state Gibbs function.

Radical species concentrations \([O], [H] \) and \([OH]\) are calculated using chemical equilibrium assumption as:

\[ [OH] = (k_2 k_4) ([H_2][O_2])^{1/2} \] (18)
\[ [O] = (k_2 k_4) ([H_2][O_2])^{1/2} \] (19)
\[ [H] = (k_2 k_4) ([k_2 k_4])^{1/2} ([H_2])^{3/2} \] (20)

In the above equations the ‘*‘ subscript denotes the reverse reaction.

2.4. Property data

All the gas mixture thermophysical properties are assumed to be functions of temperature. The curve fits for specific heats, and the data for binary diffusion coefficients given in [18] are used. Sutherland’s law is used for viscosity calculation. Gas mixture conductivity is approximated using a constant Prandtl number of 0.7.

Porous solid properties and designated baseline conditions are summarized in Tables 1 and 2.

2.5. Initial and boundary conditions

Two sets of boundary conditions for fluid and solid zones are presented hereafter. The conditions specified at the inlet are the temperature, species concentrations, and velocity of the inlet mixture, while the axial derivatives of these quantities are assumed to vanish at the domain outlet. The temperature of the solid at the leading and trailing edges are calculated accounting for the radiative and convective heat transfer between the porous matrix and its surroundings. The initial conditions for all dependent variables are set by their values at the initial time.

\[ T_g = T_{g, in}, \quad Y_i = Y_{i, in}, \quad v = 0, \quad u = u_{in}, \quad \text{at : } x = x_{in} \] (20)

\[ \frac{\partial u_i}{\partial x} = \frac{\partial Y_i}{\partial x} = 0 \quad \text{at : } x = x_{out} \] (21)

The boundary conditions for energy equation at solid region are:

\[ \left[h_{in}(T_{g, in} - T_{g, 0}) + c_e\left(T_{surr}^4 - T_{s, 0}^4\right)\right](1 - \phi) = -\lambda_{s, eff} \frac{\partial T_s}{\partial x} \quad \text{at : } x = x_0 \] (22)

\[ \left[h_{in}(T_{g, out} - T_{s, 1}) + c_e(T_{surr}^4 - T_{s, 1}^4)\right](1 - \phi) = \lambda_{s, eff} \frac{\partial T_s}{\partial x} \quad \text{at : } x = x_1 \] (23)

The axisymmetric boundary condition at the burner axis is satisfies as:

\[ \frac{\partial u_i}{\partial y} = \frac{\partial T_s}{\partial y} = \frac{\partial Y_i}{\partial y} = 0 \quad \text{at : } y = 0 \] (24)

The unsteady governing equations are solved using the following initial condition:

\[ u = u_{initial}, \quad v = v_{initial}, \quad T_g = T_{g, initial}, \quad T_s = T_{s, initial}, \quad Y_i = Y_{i, initial} \quad \text{at : } t = t_{initial} \] (25)

2.6. Solution method

The governing equations are discredited using a fully implicit, segregated, finite volume method, in which the upwind scheme is applied for the convective terms and central differences for the diffusive terms. A relative convergence criterion for numerical computation of all variables is set to \(10^{-6}\). Considering the unstable nature of flow and temperature fields in the spark and combustion initiation time period, a small time step \(10^{-3}\)
s) is set at the beginning and gradually increased to reach the steady solution.

2.7. Computational grid and grid study

To improve the accuracy of numerical results, a structured grid with more intense cells near critical zones is used. The Poisson's equation with selected weight functions for grid stretching is utilized. The schematic of the produced grid is shown in Fig. 2.

Fig. 2. Schematic of the structured and orthogonal grid.

Five different computational grids with cell amounts of 260×40, 320×30, 320×40, 380×40, and 320×50 are considered to examine the effect of cell number in both axial and radial directions. The gas and solid temperatures at the burner axis are presented in Fig. 3. Except for 260×40 case, the other temperature profiles have less than 3% difference. Therefore, the grid with 320×40 computational cells is considered as the optimum grid, considering both the accuracy and computational cost.

Fig. 3. Grid study: a) gas temperature profile, b) solid temperature profile.

3. Results and Discussion

3.1. Model validation

First, it should be noted that the published experimental investigations about hydrogen combustion in porous burners are limited, and most of them deal with the addition of hydrogen to common fuels to burn in porous burners. The validation is performed by comparison of results with experimental data of Kakutkina et al. (2006) [19]. The examined burner is assumed as a vertical cylinder filled with small grains of carborandum.

The burner configuration for the model validation is to some extent different from the
current burner configuration (Fig. 1). The main reason for this selection is the lack of experimental studies with pure hydrogen as fuel in a porous medium. Via validation of the used model (Table 3) and considering the fact that kinetic mechanism, governing equations and modeling are the same for validation case and main problem, one can guarantee the reliability of the obtained results of current study. Burner dimensions and physical properties of the filler are presented in Table 3.

Table 3: Burner geometry and physical properties of the filler material (Kakutkina et al. (2006))

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filler material</td>
<td>carborandum</td>
</tr>
<tr>
<td>Burner length</td>
<td>500 mm</td>
</tr>
<tr>
<td>Burner diameter</td>
<td>36 mm</td>
</tr>
<tr>
<td>Filler grain diameter</td>
<td>1 mm</td>
</tr>
<tr>
<td>Density</td>
<td>3150 kg/m³</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>780 J/kg.K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>16 W/m.K</td>
</tr>
</tbody>
</table>

As the porosity of the porous media hasn’t been mentioned in the original article, three different porosities equals to 0.30, 0.39 and 0.48 are considered (the highest one is for the assumption of spherical and highly ordered grains which theoretically leads to the highest possible porosity with a given grain diameter). The numerical results of the current modeling have much more agreement with the experimental data of [19] in comparison to their numerical results as shown in Fig. 4.

It should be noted that the variation range for equivalence ratio for the main modeling of current study is around stoichiometric mixture (et. 0.8-1.2). As it is obvious from Fig. 4 for the mentioned equivalence ratio interval the results for present study ($\phi=0.3$) and experimental data are lower than 9%.

3.2. Baseline simulation

3.2.1. Steady state results

Simulation parameters for the baseline conditions are summarized in Table 1. The steady state temperature profiles of the gas and solid phase are given in Fig. 5 for these conditions. The predicted gas temperature profile near the reaction zone is much broader than that in an adiabatic premixed flame. As seen in Fig. 5, based on the gas and solid phase temperatures, porous region can be divided into two zones. The first 35% of porous length is the
preheating zone where the higher solid temperature preheats the gas mixture from 298 K to approximately 1700 K. In the remaining section (reaction zone) gas temperature reaches a maximum of 2089 K and then reduces to 1820 K at the porous zone exit.

Fig. 5. Gas and solid matrix temperature profiles along the burner axis.

The axial velocity and gas temperature contours are shown in Fig. 6. Four different regions in velocity contours are recognized from this figure. A uniform velocity with formation of boundary layer in upstream of porous zone, the variation of velocity in the entrance region of porous zone due to cross sectional change, an increase in axial velocity due to combustion in reaction zone and a boundary layer flow in the downstream part, are four obvious velocity zones of the burner.

The curvilinear front of the flame and its attachment to the upper corner of the porous burner has considerable effect on the flame stability and preventing from both flashback and blow-out in a wider range of operating conditions compared to the constant cross section porous burners.

The relative magnitude of different terms in solid and gas phase energy equations are displayed in Fig.7. In the gas phase energy equation 4 different terms are varying along the channel. The energy source term is only dominant in a narrow length around the flame. The solid-gas heat exchange and gas convection terms are approximately in equilibrium down and upstream of the flame, although their zero value occurs at different locations. The change of sign of these two parameters is due to change in heat transfer direction. As it is obvious gas radiation term has negligible effect relative to other gas phase energy equation
In the solid phase energy equation the trend of heat exchange term is identical to that of the gas phase energy equation only with opposite sign. The effect of solid matrix conductivity and radiation is almost the same. This observation is due to the utilization of diffusion approximation. Also it should be noted that the share of solid radiation in the solid phase energy equation is considerable and may not be neglected especially in downstream of the flame which has the most solid temperature.

3.2.2. Transient results

The transient behavior of gas and solid temperature along the burner axis is shown in Fig. 8. As a result of higher solid conductivity, solid phase temperature profile is smoother than the gas phase. The ignition started at the beginning of time and remained for 1s (it could be easily seen from comparison of solid phase profile before and after 1s). Although the gas phase temperature doesn’t vary significantly around the time of ignition cancelling (t=1s).

As the solid conduction is related to the temperature (through radiation term modeling [20,21]), the matrix temperature profile is smoother around the maximum temperature of porous media (Fig. 8-b). The local difference between the two phase temperatures is decreased in the post-flame zone. This is due to large values of the volumetric heat transfer coefficient in the reaction zone.
The gas temperature profile is quite flat at the matrix exit. A small discontinuity in the slope of gas temperature profiles can be seen as the combustion products leave the porous region. This was expected as a result of the sudden release of gas mixture from the pores of the solid matrix; this effect was also observed in previous works, i.e. [22,23].

3.3. Effect of feed velocity

In Fig. 9 the effect of feed velocity on the gas mixture temperature is shown at the burner axis.

![Gas temperature profile](image1)

![Solid temperature profile](image2)

**Fig. 9.** Variation of a) gas, b) solid phase temperature along the axis for various feed velocities.

In this figure, the whole feed velocity range in which stable flame in stoichiometric ratio is formed has been considered (each feed velocity belongs to a specified mass flow rate). As the reactants feed velocity increases, the maximum flame temperature is intensified and the flame front moves downstream. Also it is observed that by increasing the feed velocity the temperature profile will be flattened and sudden temperature drop after maximum temperature is vanished. The reason of this behavior is that the equality of flow velocity and flame speed is the criteria for formation of a stable flame. Therefore, the increasing in feed velocity leads to increasing of flame speed which itself happens in the higher flame temperature.

3.4. NO emission

The only main pollutions in hydrogen/air combustion are NOx combinations. They are produced through three main routes, thermal mechanism (Zeldovich), N₂O and NNH routes. Among these mechanisms, thermal route is the most significant in a wide range of operating conditions. N₂O has the next important role in NO production. NNH path has the least effect except for small residence times, at high or low local.

Increasing of each one of volumetric heat coefficient or solid thermal conductivity reduce the amount of pollution production (Fig. 10). The reduction is much more pronounced for small values of these two parameters and reaches a limiting NOx production value. Although, it should be noted that this limiting value occurs for low flame temperature, which might be not practical. The effect of heat transfer parameters on the flame temperature inside the matrix and the relevance of NOx production to high temperatures is the key to this behavior.

Several parameters have influence on the variation of volumetric heat transfer coefficient including matrix specifics (et. porosity) and burner operating conditions (et. Re, Pr). As it is obvious, the results of Fig. 10 are captured by the assumption of freezing other involving parameters and examining only Hc and kₑ effects. This procedure might be not physical (all burner properties vary as a connected system for example variation of matrix
Porosity might vary HV, solid conductivity, thermal source terms and …). Although, considering one of the main advantageous of numerical simulations (which is examining the effect of involving parameters separately), valuable information about the effect of these two parameters on NOx formation is captured.

![Graphs showing NO production vs volumetric heat transfer coefficient and solid conductivity](a) and (b)

Fig. 10. NO production (ppm) versus a) volumetric heat transfer coef. b) solid conductivity.

3.5. Flammability limit

As it is discussed previously, one the major benefits of using porous burners is their stability in a wider range of operating conditions. The higher and lower bounds of feed velocity and/or stoichiometric ratio for which a stable flame could be produced are called the flammability limit. To capture the flammability chart for hydrogen/air combustion in porous burner, 60 different cases (of feed velocity and/or stoichiometric ratio variation) are studied. The variation of flame speed with stoichiometric ratio for different feed velocities is shown in Fig.11.

![Graphs showing flame velocity vs stoichiometric ratio and feed velocity](a) and (b)

Fig. 11: Flame velocity versus a) equivalence ratio b) feed velocity.

By definition, flame speed is the velocity of reactant mixture upstream of flame front. Considering the curvilinear shape of flames in most of the cases, the flame velocity is calculated by averaging over flame front length. The flame speed is increasing almost linearly with feed velocity. For each feed velocity there is a local maximum near stoichiometric mixture condition. Also it is observed that for each equivalence ratio there is a range of feed velocities in which stable flame will be formed. Next considerable observation from this figure is the growth of the difference between feed and flame
velocities by increasing the feed velocity (for high feed velocities this gap is about 50% of feed velocity).

The lower and upper bonds of feed velocity indicate the limit of flash back and blow out behaviors of the burner, respectively (the flame quenching due to the emersion of the flame from up and downstream of porous media is called flash back and blow out, respectively).

The operation diagram of studied hydrogen/air porous burner is shown in Fig. 12. The burner operating conditions which lies between flash back and blow out curves is called the stable region. Comparison with the previously obtained stable region for constant cross section area burners shows the improvement in the behavior of conical burners in increasing the range of stability, especially in flashback phenomena.

Fig. 12. Operational-stability diagram of the hydrogen/air porous burner for different operating conditions.

4. Summary and Conclusion

Premixed, laminar and unsteady combustion of hydrogen/air mixture in a solid matrix with spongy lattice is numerically simulated. The axisymmetric solid matrix is considered to be inert, isotropic and homogenous in the unsteady simulations. The burner consists of a divergent inlet followed by a constant area section. A multi-step chemical kinetics is implemented which is extracted from a detailed kinetics to calculate the NO production with high accuracy. The following observations and results are extracted from the numerical simulation:

1) By increasing the feed flow rate, the length of preheating zone, flame temperature and the NOx production is increased. These behaviors are more noticeable for used burners configuration (divergent inlet section) compared to constant area burners. The effect of flame stability which the divergent section provides to the burner causes a broader operating condition range.

2) The flammability limit is captured for all of stoichiometric ratios between 0.5 and 1.2. The flammability results showed that the widest range of feed velocities to assure a stable flame is around stoichiometric mixtures (between 0.3 to 5.0 m/s). At lean stoichiometric ratios the stable flame occurs only at low feed velocities. Form operational-stability diagram it is concluded that for rich mixtures the feed velocity which causes blow out remain almost the same as the stoichiometric condition.

3) Comparison with the previously obtained stable region for constant cross section area burners shows the improvement in the behavior of conical burners in increasing the range of stability, especially in flashback phenomena.

4) Increasing of either volumetric heat coefficient or solid thermal conductivity reduce the amount of NOx pollution production. It is observed that by increasing the value of $H_v$ and $k_s$ to 2.5 and 4 time higher values the amount of NO production reduces to 25% of its base case condition.
References

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