Numerical simulation of the combustion stability of natural gas and syngas in a surface-stabilized combustion burner

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Abstract. Surface-stabilized combustion burners is a promising combustion technique that has been studied for more than a decade. However, in the design stage of these burners is hard to determine if under certain operating conditions the burner would operate adequately. In this paper, we performed a numerical approach to predict the flame stability in a surface-stabilized combustion burner. Here we considered a numerical approach that includes simultaneous solution of mass and energy balance for both, the gas and solid phase, as well as a proper estimation of thermo-chemical and thermo-physical properties. The numerical model was validated against experimental data reported in previous studies. These data involve results with natural gas and the blending of natural gas with three high hydrogen content synthetic gases in equimolar proportions. We evaluated three synthetic gases with high hydrogen contents ranging from 60% H₂ to 75% H₂. The data also involve thermal power from 300 to 500 kW/m². The results indicate that the numerical approach described in this work predicts very well the flame stability and temperature profile within the porous media. Therefore, it can be used to study surface-stabilized combustion burners.

1. Introduction

In recent years, the high consumption of fossil fuels and the large amount of polluting emissions that contribute to the greenhouse effect such as carbon dioxide (CO₂), carbon monoxide (CO) and nitrogen oxides (NO, NO₂ and N₂O) have stimulated the search for new combustion technologies [1,2]. In the case of the domestic sector, it has been observed that surface-stabilized combustion burners are a technology that responds to the aforementioned needs and also offers the flexibility of using fuel with different chemical composition [3–6].

Surface-stabilized combustion burners or surface-radiant burners are burners that use perforated ceramic plates, ceramic foams or metal fibers to stabilize a premixed flame. The operation principle is similar to that of the burners used to determine laminar burning velocities by the heat flux method [7,8], which is illustrated in Figure 1(a). If the velocity of the air-fuel mixture has values close to the laminar burning velocity of the free flame at points downstream very close to the burner outlet plane, a "flat flame" is formed that transfers heat to the burner surface, as shown in Figure 1(b). Part of this energy heats up the surface of the burner where it is then transferred by radiation to the load. Under these operating conditions it is said that the burner is in the radiation mode.

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Increasing the output speed of the air-fuel mixture reduces the heat transfer to the burner surface, as a consequence the flame temperature - and therefore thermal NOx emissions - increases. Under these conditions it is said that the burner operates in the "blue flame mode", as illustrated in Figure 2(a). When the output speed exceeds the laminar burning velocity, the flame must be aerodynamically stabilized to prevent it from becoming unstable. At low output speeds, the flashback phenomenon can occur or the high heat transfer rate to the burner surface can cause the flame temperature to be so low that the flame blows out, as shown in Figure 2(b).

One way to avoid flame flashback and blow out is to design these burners using numerical simulation tools such as computational fluid dynamics (CFD) codes, which can provide information on the behavior of this type of flames. Up to date, most of the numerical studies on surface-stabilized combustion burners have been performed implementing one-dimensional models [10]. V.R. Kishroe et al. [11] conducted numerical studies with a three-dimensional model that allowed to predict with great precision the experiments carried out under the same operating conditions. It was reported that it is even possible to simulate flames with cellular structures. However, compared to one-dimensional models, the three-dimensional model employed by V.R. Kishroe et al. requires a very high computation cost.

The aim of this work is to predict numerically the combustion performance of low calorific value fuels in a ceramic surface-stabilized combustion burner, in particular, to predict the effects of substituting natural gas (NG) with synthetic gas (SG) on flame stability. In this paper, we studied three synthetic gases (SGs) with high hydrogen contents ranging from 60% H₂ to 75% H₂ implementing a low computational cost model. The experimental data to validate the results were reported by the authors in a previous study [12]. The results indicate that the numerical approach implemented in this work allows to predict the flame stability in a surface-stabilized combustion burner, as well as other properties of the system such as the temperature profile inside the porous matrix.
2. Numerical model

Figure 3 shows the experimental burner that we used in a previous study to determine the combustion stability, pollutant emissions and the temperature distribution within the porous media [12]. The burner consists of a monolithic honeycomb-type cylindrical structure with parallel channels of square section of 1 mm² and a cell density of 18 CPI (cells per inch). The diameter of the porous media is 70 mm and the void fraction is 0.62. The porous material was fabricated from alumina (Al₂O₃) and has a thickness of 25 mm.

![Experimental burner](image)

Figure 3. (a) Experimental burner. 1. Porous media, 2. Burner structure, 3. Slits for temperature probing, 4. Mixing chamber. (b) Schematic representation of the porous matrix [12].

In the experimental unit, the fuel and air entered the mixing chamber separately. High-purity certified gases (99% purity) were used to simulate the SGs. Table 1 lists the volumetric compositions of the fuel mixtures evaluated in this work.

|        | GN  | 50SG1 | 50SG2 | 50SG3 |
|--------|-----|-------|-------|-------|
| CH₄    | 94.68 | 47.34 | 47.34 | 47.34 |
| C₂H₆   | 2.37  | 1.19  | 1.19  | 1.19  |
| C₃H₈   | 0.81  | 0.40  | 0.40  | 0.40  |
| n-C₃H₈ | 0.15  | 0.08  | 0.08  | 0.08  |
| i-C₃H₈ | 0.16  | 0.08  | 0.08  | 0.08  |
| CO₂    | 0.56  | 0.28  | 0.28  | 0.28  |
| N₂     | 1.27  | 0.63  | 0.63  | 0.63  |
| H₂     | --    | 30.00 | 33.35 | 37.50 |
| CO     | --    | 20.00 | 16.85 | 12.50 |

Numerical simulations for the different fuel mixtures were performed in Ansys Fluent using detailed chemical kinetics (GriMech 3.0). Figure 4 presents the computational domain implemented in this work. The resultant grid resolution was 0.1 mm³ x 0.1 mm³ x 0.1 mm³. As can be observed from Figure 4, our numerical approach consists in analyzing a section of the burner.

The boundary condition “velocity inlet” was configured to achieve 300, 400, and 500 kW/m². Governing equations are mass continuity, Navier-Stokes, species conservation and state equations. Equation (1) is continuity equation:

\[
\frac{\partial}{\partial t} \left( \gamma \rho \right) + \nabla \cdot \left( \gamma \rho \mathbf{u} \right) = 0, \tag{1}
\]
where \( \gamma \) is the porosity of the porous media, \( \rho_g \) is the fuel-air mixture density and \( \mathbf{u} \) is the mixture velocity. Equation (2) is momentum equation:

\[
\frac{\partial}{\partial t} (\gamma \rho_g \mathbf{u}) + \nabla \cdot (\gamma \rho_g \mathbf{u} \mathbf{u}) = -\gamma \nabla p + \nabla \cdot (\gamma \mathbf{r}) + R
\]

\[
R = -\left(\frac{1}{\alpha} + \frac{1}{2} C_2 \rho_g |\mathbf{u}|^2\right) \mathbf{u},
\]

where \( R \) represents the inertial and viscous resistance generated by the porous matrix. \( 1/\alpha \) is the viscous resistance factor and \( C_2 \) is the inertial resistance factor. These properties were determined experimentally. Equation (3) is species equation:

\[
\frac{\partial}{\partial t} (\gamma \rho_g Y_k) + \nabla \cdot (\gamma \rho_g \mathbf{u} Y_k) = -\nabla \cdot (\gamma \rho_g Y_k \mathbf{v}_i) + \gamma (\omega_k W_k)
\]

\[
\mathbf{v}_i = \mathbf{u}_i - \mathbf{u},
\]

where \( Y_k \): mass fraction of species \( k \), \( \mathbf{v}_i \): diffusive velocity of species \( k \), \( \mathbf{u}_i \): relative velocity of species \( k \), \( \omega_k \): reaction rate of species \( k \). \( W_k \) is the molar mass of species \( k \). Equation (4) is energy equation (gas phase):

\[
\frac{\partial}{\partial t} \left[ (1 - \gamma) \rho_g C_{p_g} T_g \right] + \nabla \cdot \left[ (1 - \gamma) \rho_g \mathbf{C}_{p_g} \nabla T_g \right] = \nabla \cdot \left[ (1 - \gamma) k_g^S \mathbf{C}_{p_g} \nabla T_g \right] + h_{gs} A_{gs} (T_g - T_s)
\]

\[
k_g^S = k_g + \sum_k \rho_g \mathbf{C}_{p_g} \mathbf{D}_{Tk} h_{v} = h_{gs} A_{gs},
\]

where \( C_{p_g} \) and \( T_g \) are the specific heat and gas phase temperature, respectively. \( k_g^S \) is the heat transfer coefficient of the gas phase. Where \( k_g \) is the thermal conductivity of the gas phase and \( \mathbf{D}_{Tk} \) are the thermal diffusion coefficients. \( h_{v} \): volumetric heat transfer coefficient between the gas and solid phase. Equation (5) energy equation (solid phase):

\[
\frac{\partial}{\partial \tau} \left[(1 - \gamma) \rho_s C_{p_s} T_s \right] = \nabla \cdot \left[(1 - \gamma) k_s^S \mathbf{C}_{p_s} \nabla T_s \right] + h_{gs} A_{gs} (T_g - T_s)
\]

\[
k_s^S = k_C + k_R,
\]

where \( k_s^S \): is the heat transfer coefficient of the solid phase, \( k_C \) is the thermal conductivity of the porous matrix and \( k_R \) is the radiation heat transfer coefficient.

Figure 4. Schematic of computational domain.
3. Results and discussions

Figure 5 shows the flame stability limits that were obtained experimentally, which correspond to NG and the NG-SGs blends. Figure 5 represents several operating conditions that were evaluated. Three types of operating conditions can be observed in Figure 5: the blowout region (to the left of the blowout limit, BL), the flashback region (to the right of the flashback limit, FL) and the stable region (between the BL and FL).

The trends described above were also registered numerically, as shown in Figure 6 and Figure 7.

Numerically, flashback and blowout phenomena were identified analyzing the temperature profile of both, gas and solid phase. Figure 7(a) shows the typical temperature profile obtained for the operating conditions that lead to flashback. Similarly, the operating conditions that lead to blow out exhibit a constant temperature profile with a value of inlet temperature. On the other hand, Figure 7(b) shows the typical temperature profile obtained for stable operating conditions. Therefore, from Figures 6 and Figure 7 it can be concluded that the numerical approach implemented in this work can be used to analyze flame stability in a surface-stabilized combustion burner.
4. Conclusions

In this work, the flame stability achieved by a surface-stabilized combustion burner operating with NG and the blending of NG with three high hydrogen content SG in equimolar proportions was studied numerically. It was possible to show that the flame stability in these types of burners can be predicted if the numerical model includes the simultaneous solution of mass and energy balance for both, the gas and solid phase, as well as a proper estimation of thermo-chemical and thermo-physical properties. Following the numerical approach describe in this study, future work can be performed in order to better understand the effect of other important parameters such as porous media material, porosity, burner design, and burner-load interaction.

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