Stabilization Operation Region for a Reciprocal Flow Burner

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Abstract: - A reciprocal gas flow burner is computationally simulated for obtaining its stable operation region in terms of equivalence ratio and filtration velocity, for two energy losses configurations schemes. Equivalence ratio and filtration velocity were considered over the range [0.1, 1.0] and [0.25, 1.0] (m/s). Lateral heat losses were studied at two scenarios: reactor coupled with and without heat exchangers. Results demonstrated increased stabilization in temperature profile, thus increased stabilization region for the reactor coupled with heat exchangers.

Key-Words: - Reciprocal Flow Burner (RFB); porous media; filtration combustion; numerical simulation

1 Introduction
Because of the pressure derived from the need to lower emissions and increase efficiency in the combustion of fossil fuels, new methods of combustion and advanced burner designs are being sought. A porous medium burner can provide a good solution because it has a number of advantages compared to conventional combustion with a free flame: large power variation range, high efficiency, compact structure with very high energy concentration per unit volume, extremely low CO and NOX emission over a wide range of thermal loads, stable combustion over a wide range of equivalence ratios, 0.4 < Φ < 0.9 [1]. All the arguments mentioned above are driving the current development of these kinds of burners which have already found several important industrial applications [2, 3].

The problem of gas combustion in inert porous media has been studied intensively both theoretically and experimentally. The most important results of both research methodologies have been summarized [4, 5]. One of the most important problems of porous media burners is stabilization of the flame in a specific zone of the inert porous medium. It is also important for the static combustion front to have some predefined characteristics to be able to maximize the efficiency of the burner and minimize CO and NOX emissions [2]. For that purpose four different flame control methods have been developed. The first method considers the formation of two layers of the porous medium in which the modified Peclet number is less than (first layer) or greater than (second layer) 65 [1, 2, 6]. The second method considers cooling of the postcombustion zone [7, 8]. The third method allows retaining the flame in a specific zone of the porous medium by means of a periodic exchange of the mixture inlet and the exhaust of the combustion gases [9, 10]. Finally, the fourth method of flame stabilization employs a porous body with non-constant cross sectional area [11]. The motion of the combustion zone results in positive or negative enthalpy fluxes between the reacting gas and solid porous media. As a result, observed combustion temperatures can significantly differ from adiabatic predictions based on the enthalpy of the initial reactants and is controlled mainly by reaction chemistry and heat transfer mechanism. Upstream wave propagation, countercurrent to the gas flow, results in superadiabatic combustion temperature [4] while downstream propagation of the wave leads to combustion in the superadiabatic regime with temperatures much in excess of the adiabatic temperature [10]. Superadiabatic combustion significantly extends conventional flammability limits to the region of ultra low heat content mixtures.

Reciprocating superadiabatic combustion of premixed gases in porous media is a new porous burner technology. With embedded devices periodically switching the direction of the premixed gases, an RFB burner not only has the advantages of a porous media burner with one-directional flow, but also some more attractive combustion characteristics. This type of technology finds diverse applications nowadays: fluid heaters, thermophotovoltaics systems amongst others. The present work has as objective the study of a RFB with porous media body conformed of alumina spheres with 5.6 mm diameter that can be used as energy source for a TPV system.

TPV technology is based in direct conversion from thermal radiation to electric energy through photovoltaic cells (PV). These systems are composed of a thermal radiation source, a selective photon
emitter, a band photon filter and a photovoltaic converter. The selective emitter and filter adapt the radiation spectrum to a maximum photon absorption in PV cells.

2 Problem Formulation

The reciprocal flow burner consists of a quartz tube of length $L = 50$ (cm), outer diameter $d_t = 50$ (mm), filled with randomly disposed alumina spheres of diameter $d_0 = 5.6$ (mm), giving volumetric porosity $m = 0.4$.

During operation gas mixture is periodically reversed at a constant time period called half-cycle time $t_c$.

Two cases of lateral energy losses were studied for parameter $\beta$ (W/m$^3$K$^1$). First configuration considered two heat exchangers of length $L_L = L_R = 12$ (cm) placed at the left and right reactor ends. Central part was kept under isolation in order to maintain constant temperature profiles in this region. Second reactor configuration was not coupled with heat exchangers and thus, according to an energy balance to the reactor, volumetric heat losses are function of the temperature $\beta = f(T)$ as shown in Eq. (1). Fig. 1 shows reactor left, middle and right regions considered.

$$\beta = \frac{4}{d_{alum}} \left( \varepsilon \cdot \kappa \cdot \sigma (T_s^n - T_{ext}^n) + \alpha_{out} (T_s - T_{ext}) \right)$$ (1)

2.1 Governing equations.

Inside reactor RFB, temperature and composition profiles are assumed one-dimensional. Chemical reaction of combustion (CH$_4$/Air) is homogenous and one-step kinetics model of Eq. (2) applies:

$$CH_4 + 2(1 + \phi)O_2 + 3.76N_2 \rightarrow CO_2 + 2H_2O + 2\phi O_2 + 7.52(1 + \phi)N_2$$

Where $\Phi = (1 + \phi)^{-1}$ is the equivalence ratio.

2.1.1 Continuity Equation

$$\frac{\partial \left( \rho_g \cdot u_g \right)}{\partial z} = 0$$ (3)

$u_g$ filtration velocity of gas mixture.

Here is assumed ideal gas behavior due to operating conditions of low pressures (1 atm) and high temperatures (1300 – 1800 K):

$$\rho_g = \frac{p \cdot M}{R \cdot T_g}$$ (4)

$p$ atmospheric pressure (atm), $M$ average molar mass of gas mixture (g/mol), $R$ universal gas constant (atm·L/mol·K), $T_g$ gas phase temperature (K).

2.1.2 Mass conservation of fuel.

$$\rho_g \frac{\partial w_i}{\partial t} + \rho_g \cdot u_g \frac{\partial w_i}{\partial z} = \frac{\partial \rho_g \cdot D_{ax} \frac{\partial w_i}{\partial z}}{\partial z} + r_i$$ (5)

$$D = D_g + D_d$$ (6)

$$D_d = 0.5 \cdot u_g \cdot d_0$$ (7)

With $w_i$ mass fraction of methane, $D_g$ gas diffusivity, $D_d$ axial dispersion coefficient. Consumption rate of fuel is given by Eq. (8):

$$r_i = -K_0 \cdot w_i \cdot \rho_g \exp \left( -E / R \cdot T_g \right)$$ (8)

Frequency factor and activation energy are $K_0 = 2.6 \cdot 10^8$ (1/s), $E/R = 15643.5$ (K).

2.1.3 Gas phase energy conservation.

Heat transfer mechanisms by convection, conduction and dispersion are considered, and additional term of heat release due to reaction of combustion is included in formulation:
\[ \rho_g \cdot c_p \cdot \frac{\partial T_g}{\partial t} + c_p \cdot \rho_g \cdot u_g \cdot \frac{\partial T_g}{\partial z} = 0 \]  
(9)

\[ \frac{\partial}{\partial z} \left( \lambda_g + D_d \cdot \rho_g \cdot c_p \right) \frac{\partial T_g}{\partial z} = \frac{\alpha_{vol}}{m} \left( T_s - T_g \right) - r_i \cdot \Delta h_c \]  

Boundary and initial conditions are given by:

\[ \forall t, \quad \left. \frac{\partial T_g}{\partial z} \right|_{z=0,L} = 0 \]  
(10)

\[ t = 0, \quad T_g \big|_{z=z_L} = T_0 \]  
(11)

Where \( c_p, \lambda_g \) heat capacity and conductivity of gas mixture, \( \alpha_{vol} \) volumetric heat transfer coefficient between solid and gas phases, \( \Delta h_c \) heat of reaction, \( T_0, T_s \) initial and solid temperature. Physical properties of gas mixture are correlated by Eqs. (12)-(15):

\[ c_p = 947.0 \cdot \exp \left( 1.83 \cdot 10^{-4} \cdot T_g \right) \]  
(12)

\[ \lambda_g = 4.82 \cdot 10^{-7} \cdot c_p \cdot T_g^{0.7} \]  
(13)

\[ \alpha_{vol} = \frac{\lambda_g \cdot 6(1-m)}{d_o^2} \left[ 2 + 1.1 \left( \frac{\mu \cdot c_p}{\lambda_g} \right)^{1/3} \right] \left( \frac{\rho_g \cdot m \cdot u_g \cdot d_o}{\mu} \right)^{0.6} \]  
(14)

\[ \mu = 3.37 \cdot 10^{-7} \cdot T_g^{0.7} \]  
(15)

With \( \mu \) gas mixture viscosity.

2.1.4 Solid phase energy conservation.

Heat transfer by conduction, radiation and interphase heat exchange are included:

\[ (1-m) \rho_s \cdot c_s \cdot \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \left( \lambda_s \frac{\partial T_s}{\partial z} \right) \]  
(16)

\[ \alpha_{vol} \left( T_g - T_s \right) - \beta \left( T_s - T_{\text{ea}} \right) \]

\[ \lambda_s = 0.01 \cdot \lambda_g + \frac{32 \cdot \sigma \cdot d_o \cdot m \cdot \varepsilon}{9(1-m)} T_s^3 \]  
(17)

Initial and boundary conditions given by:

\[ T_s \big|_{z=0} = \begin{cases} T_{\text{ign}}, & z \in \left[ z_s, z_L \right] \\ T_0, & z \notin \left[ z_s, z_L \right] \end{cases} \]  
(18)

Here \( T_{\text{ign}} \) Ignition temperature, \( \sigma \) Stefan-Boltzmann constant, \( c_s, \lambda_s \) heat capacity and thermal conductivity of solid phase correlated by:

\[ c_s = 29.567 + 2.61177 \cdot T_s - 0.00171 \cdot T_s^2 + 3.382 \cdot 10^{-7} \cdot T_s^3 \]  
(20)

\[ \lambda_s = -0.21844539 + 0.00174653 \cdot T_s + 8.2266 \cdot 10^{-8} \cdot T_s^2 \]  
(21)

2.2 Numerical solution of equations.

Mathematical model are discretized by finite differences method through implicit scheme and its solution reached by algorithm TDMA. Uniform grid with 801 nodes and time step \( \Delta t = 0.01 \) (s) gave solution independence.

2.3 Numerical validation.

Validation of numerical solution was reached through replication of results published in [10]. Fig. 2 presents gas and solid temperature profiles for \( \phi = 2.33, u_g = 0.5 \) (m/s), \( t_c = 10 \) (s). Temperature distributions found are in concordance to the results of Contarin et al [10].

![Figure 2: Gas and solid temperature profiles for validation, \( \phi = 2.33, u_g = 0.5 \) (m/s), \( t_c = 10 \) (s).](image)

3 Problem Solution

3.1 Stable and unstable cases.

Fig 1 shows stable solid temperature evolution. Stationary temperature profiles were reached within the first 2000 (s). Situations depicted in Fig. 2 and Fig. 3 exhibits instabilities in the temperature profile which leads to unstable reactor operation. These scenarios are
to be avoided, thus it is necessary to obtain the stability region for safe reactor operation.

3.2 Numerical simulation method.
Simulations were performed in the space $u_g \in [0.25, 1]$ (m/s), $\Phi \in [0.1, 1]$, varying operational variables at steps of size $\Delta u_g = 0.02$ (m/s), $\Delta \Phi = 0.02$. Initially, for each case, an ignition profile is imposed in the central region of the reactor. A case for which the triplet $(u_g, \Phi, \beta)$ produces stable temperature profiles were recognized if variation of maximum temperature levels and position are kept under tolerances: $\Delta T_{s,\text{Max}} \leq 2$ (K), $\Delta z_w \leq 10^{-5}$ (m). Unstable cases were detected if $T_{s,\text{Max}} \leq 800$ (K), condition of Fig. 2, or $z_{w,\text{L}} < 0.12$ (m), $z_{w,\text{R}} > 0.38$ (m) case of Fig. 3. The stability criteria were evaluated each 500 (s) starting from simulation time 2000 (s). Simulation time was extended until a stopping criterion was found, point at which a new triplet $(u_g, \Phi, \beta)$ was sought for evaluation.

3.3 Stability region.
Fig. 4 presents stable operation region in the $u_g$-$\Phi$ plane for RFB reactor as function of type of energy losses. Firing rate contours are included for comparison of potency ranges between the two regions. Results indicate a much larger stable operation region for the reactor coupled with heat exchangers. Firing rate range found for this type of energy losses was $[50, 694]$ (kW/m$^2$). Reactor with natural energy losses provides a much smaller potency range $[64, 227]$ (kW/m$^2$). Similar lower region bound was found in both configurations, while the upper region bound was found in both configurations, while the upper region bound makes the most significant increment in operation range.
4 Conclusion
A reciprocal flow burner for methane/air mixtures was computationally simulated for obtaining its stability operation region as function of energy losses to the extern media. Results indicate a much larger operation range when heat exchangers are coupled at the reactors left and right regions compared to operation with natural heat losses. Similar lean flammability limits were found for both configurations whereas upper bound is noticeable higher for reactor coupled with heat exchangers.

5 Nomenclature

5.1 List of symbols

- \(c\) Specific heat.
- \(d_0\) Particle diameter.
- \(d_{sub}\) Inner diameter of the tube.
- \(D_d\) Dispersion coefficient.
- \(D_g\) Molecular diffusivity coefficient.
- \(E\) Activation energy.
- \(K_0\) Frequency factor.
- \(L\) Tube length.
- \(m\) Porosity.
- \(M\) Average gas molar mass.
- \(p\) Atmospheric pressure.
- \(R\) Universal gas constant.
- \(r_i\) Consumption rate of methane.
- \(t\) Time.
- \(u\) Filtration velocity.
- \(w_i\) Mass fraction of methane.
- \(z\) Axial direction.

5.2 Greek letters.

- \(\alpha_{out}\) Heat transfer coefficient at cylindrical mantle surface.
- \(\alpha_{vol}\) Volumetric heat transfer coefficient between phases.
- \(\beta\) Volumetric energy losses coefficient to the environment.
- \(\rho\) Density.
- \(\varepsilon\) Emissivity of alumina spheres.
- \(\phi\) Fraction of excess air.
- \(\Phi\) Equivalence ratio.
- \(\lambda\) Thermal conductivity.
- \(\Delta h_c\) Specific reaction heat of methane.
- \(\mu\) Gas mixture viscosity.
- \(\kappa\) Transmissivity of quartz tube.
- \(\sigma\) Stefan-Boltzmann constant.

5.3 Subscripts.

- \(w\) Relative to temperature peak.
- \(L\) Left.
- \(M\) Middle.
- \(R\) Right.
- \(Max\) Maximum.
- \(s\) Medium porous.
- \(g\) Gaseous Mixture.
- \(0\) Initial.
- \(ign\) Ignition.

References:


