

A FLAMELET MODEL FOR DIFFUSION FLAMES IN POROUS MEDIA

Max Akira Endo Kokubun

Instituto Nacional de Pesquisas Espaciais,
Rod. Presidente Dutra, km 40 - Cachoeira Paulista/SP,
max@lcp.inpe.br

Fernando Filho Fachini

Instituto Nacional de Pesquisas Espaciais,
Rod. Presidente Dutra, km 40 - Cachoeira Paulista/SP,
fachini@lcp.inpe.br

Abstract: *In the present work, a flamelet-type modeling is attempted for describing the small-scale features of liquid fuel combustion inside a porous inert media. The flamelet theory has been formulated for describing a flame element for turbulent combustion, and is one of the tools for studying flame dynamics. A combustion established inside a porous medium has some features that are not observable at free propagating combustion. First of all, one must consider that the porous matrix acts as a resistance force to the flow due to the tortuosity, which is taken into account in the conservation equations. Also, the porous matrix interacts directly with the system recirculating the heat upward and downward the reaction zone, leading to a more efficient burning process, and, consequently, with less pollutant combustion emission. We are considering a combustion front propagating inside a porous matrix. As the front advances, the liquid fuel ahead of it evaporates, and hence, sustains the combustion. In this work, we will attempt to apply the flamelet modeling idea to the combustion front propagating inside a porous medium.*

Keywords: *diffusion flames, porous media.*

1 Introduction

Combustion phenomena inside porous medium have been studied for decades (Howell *et al.*, 1996; Kayal and Chakravarty, 2005). Such interest may be explained by the enormous amount of applications encountered for these combustion systems, ranging from industrial chambers, passing by in-situ oil recovery, to household applications, etc (Mujeebu *et al.*, 2008). One of the main features related to porous media confined combustion is the heat recirculation from downstream to upstream the flame, such characteristic provides an excess enthalpy to preheat the reactants, leading then to a more efficient combustion process, and even making it possible to burn lean mixtures.

Schult *et al.* (Schult *et al.*, 1996) studied forced forward smolder combustion inside a porous cylindrical samples closed to the surrounding environment with the injection of gas being performed in one end of the sample, and using asymptotic methods they found two traveling smolder waves with different structures, characterized by the reaction zone and the zone due to the heat transfer between the solid and the gas. An extent of such work has been performed by Akkutlu and Yortsos (Akkutlu and Yortsos, 2003) with the consideration of heat losses during the process. The stability of the traveling waves also has been analyzed. Both works consider premixed combustion, as they look to large-scale processes.

Studies concerning porous media combustion, have been conducted for several years. Transport properties have been analyzed, mainly. Raju and T'ien studied a counterflow configuration with the liquid fuel (ethanol) inside the porous matrix and analyzed capillarity and mass and heat transport effects (Raju and T'ien, 2007). A two-phase vapor-liquid region has been found close to the wick surface just above the pure liquid region.

The present study analyzes the establishment of the flame inside the porous medium.

2 Formulation

When we look at the problem using the flamelet theory, we obtain a impinging flow configuration inside a porous medium. The geometry is the same studied by (Raju and T'ien, 2007), but we consider the establishment of the flame inside the porous medium. A representative scheme for the proposed configuration is given by:

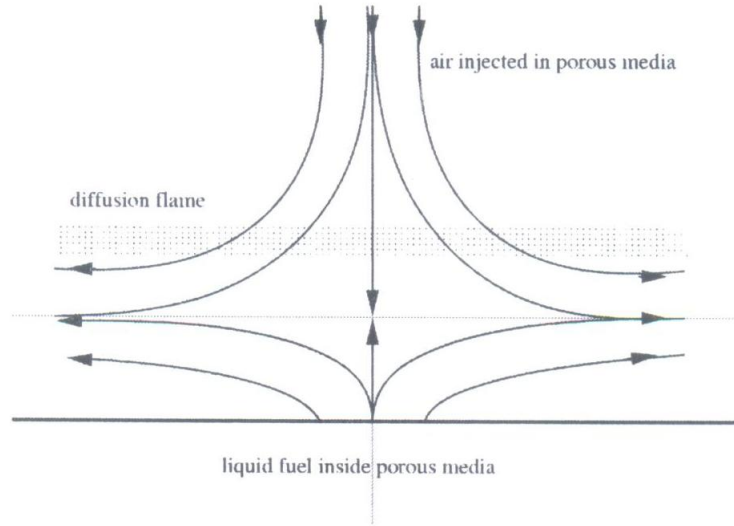


Figure 1: Counterflow inside a porous medium

The governing equations for the gas phase are the following:

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

$$\rho \bar{u} \frac{\partial \bar{u}}{\partial \bar{x}} + \rho \bar{v} \frac{\partial \bar{u}}{\partial \bar{z}} = -\varepsilon \frac{\partial \bar{p}}{\partial \bar{x}} + \frac{\partial}{\partial \bar{z}} \left(\bar{\mu} \frac{\partial \bar{u}}{\partial \bar{z}} \right) - \varepsilon \bar{\mu} \frac{\bar{u}}{K} \quad (2)$$

$$\varepsilon \rho \bar{v} \frac{\partial Y_F}{\partial \bar{z}} = \varepsilon \frac{\partial}{\partial \bar{z}} \left(\rho \bar{D}_F \frac{\partial Y_F}{\partial \bar{z}} \right) - \varepsilon \bar{w}_F \quad (3)$$

$$\varepsilon \rho \bar{v} \frac{\partial Y_O}{\partial \bar{z}} = \varepsilon \frac{\partial}{\partial \bar{z}} \left(\rho \bar{D}_O \frac{\partial Y_O}{\partial \bar{z}} \right) - \varepsilon s \bar{w}_F \quad (4)$$

$$\varepsilon \rho \bar{v} c_p \frac{\partial T_g}{\partial \bar{z}} = \varepsilon \frac{\partial}{\partial \bar{z}} \left(\bar{\lambda}_g \frac{\partial T_g}{\partial \bar{z}} \right) + \varepsilon Q \bar{w}_F + h_v (T_s - T_g) \quad (5)$$

The parameter ε is the medium porosity. It's given by the ratio between the porous volume and the total solid volume. In equation (2) the term $-\bar{\mu}(\bar{u}/K)$ is the Darcy term and it corresponds to a resistive force to the movement of a fluid particle due to the existence of the tortuous pores channels. K is the medium permeability and its value ranges from 10^{-7} and 10^{-12} and its measured in m^2 . The above set of equations dictates the behavior of the oxidant and fuel in gaseous phase.

In the portion of the solid phase filled with gas, the energy conservation equation is

$$0 = (1 - \varepsilon) \frac{d}{d\bar{z}} \left(\bar{\lambda}_s \frac{dT_s}{d\bar{z}} \right) - h_v (T_s - T_g) \quad (6)$$

The parameter h_v is the volumetric surface-convective coefficient and it quantifies the heat exchange between phases. In equations (3) to (5), the term \bar{w}_F represents the reaction rate.

In this model, the infinite fast chemical reaction is adopted, then it is not necessary to detail \bar{w}_F .

The conservation equations for the liquid phase, that feels the porous media, are:

$$\rho_l \bar{v}_l = \bar{m} \quad (7)$$

$$\varepsilon \rho \bar{v} c_l \frac{\partial T_l}{\partial \bar{z}} = \varepsilon \bar{\lambda}_l \frac{\partial^2 T_l}{\partial \bar{z}^2} + h_l (T_s - T_l) \quad (8)$$

In the portion of the solid matrix filled with liquid fuel, the energy conservation equation is:

$$0 = (1 - \varepsilon) \bar{\lambda}_s \left(\frac{d^2 T_s}{d\bar{z}^2} \right) - h_l (T_s - T_l) \quad (9)$$

To better analyze the problem, we perform a change of variables and make them non-dimensional, as given by:

$$u = a x U(z), \quad \varrho v = -a^{1/2} f,$$

$$p_\infty - p = (1/2) a^2 \left(1 + \frac{1}{\Gamma} \frac{l_c^2}{aK} \right) [x^2 + F(z)], \quad \eta = a^{1/2} \int_0^z \varrho dz \quad (10)$$

in which $u \equiv \bar{u}/\bar{v}_\infty$, $v \equiv \bar{v}/\bar{v}_\infty$, $p \equiv \bar{p}/(\rho_\infty v_\infty^2)$, $\varrho \equiv \rho/\rho_\infty$, $\varrho_l \equiv \rho_l/\rho_\infty$, $x \equiv \bar{x}/l_c$, $z \equiv \bar{z}/l_c$, $U \equiv U^*/d\bar{u}/d\bar{x}|_\infty$, $a \equiv (l_c/\bar{v}_\infty)d\bar{u}/d\bar{x}|_\infty$.

The characteristic length scale l_c is chosen in a such way that $l_c = \alpha_s^*/\bar{v}_\infty$, where $\alpha_s^* \equiv \bar{\lambda}_s/(\rho_\infty c_p)$ and Γ will be defined later.

Substituting into the governing equations, we obtain:

$$U = \frac{df}{d\eta} \quad (11)$$

$$\frac{Pr}{\Gamma} \frac{d^3 f}{d\eta^3} + f \frac{d^2 f}{d\eta^2} - \left(\frac{df}{d\eta} \right)^2 - \varepsilon \frac{Pr}{\kappa \Gamma} \frac{1}{\varrho^2} \frac{df}{d\eta} = -\varepsilon \frac{1}{\varrho} \left(1 + \frac{1}{\kappa \Gamma} \right) \quad (12)$$

$$\frac{1}{\Gamma} \frac{d^2 y_F}{d\eta^2} + L_F f \frac{dy_F}{d\eta} = \frac{L_F w_F}{a \varrho} \quad (13)$$

$$\frac{1}{\Gamma} \frac{d^2 y_O}{d\eta^2} + L_O f \frac{dy_O}{d\eta} = S \frac{L_F w_F}{a \varrho} \quad (14)$$

$$-\varepsilon f \frac{d\theta_g}{d\eta} = \varepsilon \frac{1}{\Gamma} \frac{d}{d\eta} \left(\varrho \frac{d\theta_g}{d\eta} \right) + \varepsilon \frac{w_f q}{a \varrho} + N_v \frac{1}{a \varrho} (\theta_s - \theta_g) \quad (15)$$

$$0 = (1 - \varepsilon) \frac{\partial}{\partial \eta} \left(\varrho \frac{\partial \theta_s}{\partial \eta} \right) - N_v \frac{1}{a \varrho} (\theta_s - \theta_g) \quad (16)$$

for the gas phase.

And for the liquid phase:

$$\varrho_l v_l = \frac{\bar{m}}{\rho_\infty \bar{v}_\infty} \equiv \dot{m} \quad (17)$$

$$\varepsilon K \frac{d^2 \theta_l}{dz^2} - \varepsilon M \frac{d\theta_l}{dz} = -N_l (\theta_s - \theta_l), \quad (18)$$

$$(1 - \varepsilon) \frac{d^2 \theta_s}{dz^2} = N_l (\theta_s - \theta_l) \quad (19)$$

in which are kept the spatial variable z ; the variable η is used only in the portion of the porous medium filled with gas. The parameters in equations (18) and equation (19) are defined as

$$M \equiv \dot{m} (c_l / c_p), \quad N_l \equiv h_l \bar{\lambda}_s / (\rho_\infty \bar{v}_\infty c_p)^2 = (h_l / h_v) N_v \\ K \equiv (\lambda_l / \bar{\lambda}_s),$$

The boundary conditions in the inlet oxidant gas phase are

$$U = \frac{df}{d\eta} - 1 = \theta_g - 1 = \theta_s - 1 = y_O - 1 = y_F = 0 \quad \text{for } \eta = \infty \quad (20)$$

at the liquid surface $\eta = z = 0$, the boundary conditions are

$$\frac{df}{d\eta} = \theta_g - \theta_0 = \theta_s - \theta_{s0} = y_O = y_F - y_{F0} = 0, \quad \frac{1}{\Gamma} \frac{1}{L_F} \frac{dy_F}{d\eta} \Big|_{\eta=0^+} = (1 - y_{F0}) f_0, \\ \frac{1}{\Gamma} \frac{d\theta_g}{d\eta} \Big|_{\eta=0^+} = -l f_0 + \frac{K}{a^{1/2}} \frac{d\theta_l}{dz} \Big|_{z=-z_b} - \frac{N_l}{a^{1/2}} \int_{-z_b}^0 (\theta_s - \theta_l) dz, \quad (21)$$

in which $l \equiv L / (c_p T_\infty)$.

The Clapeyron relation relates the fuel mass fraction at the liquid surface with the corresponding temperature as

$$y_{F0} = \exp \left[l_R \left(\frac{1}{\theta_{g0}} - \frac{1}{\theta_b} \right) \right] \quad (22)$$

the parameter l_R is defined as $l_R \equiv L / (RT_\infty) = l\gamma / (\gamma - 1)$. The velocity of the fuel in the gas phase at the liquid surface is related with the vaporization rate as

$$\varrho_0 \cdot v_{0+} = \varrho_{l0} \cdot v_{l0-} = \dot{m} = -a^{1/2} f_0 \quad (23)$$

The velocities v_{0-} and v_{0+} represent the velocities of the liquid fuel and vapor fuel at the interface.

The boundary conditions in the inlet liquid fuel are ($z \rightarrow -\infty$)

$$v_l - v_{l-\infty} = \theta_l - \theta_{-\infty} = \theta_s - \theta_{-\infty} = \varrho_l - (\rho_{l-\infty} / \rho_\infty) = y_F - 1 = 0 \quad (24)$$

With the conservation equations in all phases established and in a non-dimensional form, the proposed model will be tested with the use of experimental parameters in order to validate the approach.

Acknowledgments

The authors would like to thank Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial support, and Instituto Nacional de Pesquisas Espaciais (INPE) for providing the structure for the current research.

References

- Akkutlu, I.Y. and Yortsos, Y.C., 2003, "The dynamics of in-situ combustion fronts in porous media", *Combustion and Flame*, Vol. 134, pp. 229-247.
- Howell, J.R., Hall, M.J. and Ellzey, J.L., 1996, "Combustion of hydrocarbons fuels within porous inert media", *Progress in Energy and Combustion Science*, Vol. 22, pp. 121-145.
- Kayal, T.K., and Chakravarty, M., 2005, "Combustion of liquid fuels inside inert porous media: an analytical approach", *International Journal of Heat and Mass Transfer*, Vol. 48, pp. 331-339.
- Mujeebu, M.A., Abdullah, M.Z., Abu Bakar, M.Z., Mohamad, A.A., Muhad, R.M.N., and Abdullah, M.K., 2008, "Combustion in porous media and its applications - A comprehensive survey", *Journal of Environmental Management*, Vol. 2, pp. 1-26.
- Raju, M.P. and T'ien, J.S., 2007, "Heat and Mass Transports in a One-Dimensional Porous Wick Driven by a Gas-Phase Diffusion Flame", *Journal of Porous Media*, Vol. 10, pp. 327-342.
- Schult, D.A., Matkowsky, B.J., Volpert, V.A., and Fernandez-Pello, A.C., 1996, "Forced Forward Smolder Combustion", *Combustion and Flame*, Vol. 104, pp. 1-26.