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Investigation of unsteady behaviors of forward and opposed flow combustion of solid fuel

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ABSTRACT

We theoretically examine the characteristics of a combustion wave of solid fuel in a porous medium. We consider two problems (i) a sample is ignited at one of the either ends and (ii) a sample is ignited around the middle. Depending on the ignition process, forward and opposed modes of a combustion wave are found in the first problem while they simultaneously occurred in the second problem. Firstly, we make a comparative study between forward and opposed modes and secondly, we investigate the combined effects of these modes. Analytical expressions of combustion characters, namely, the moving speed of the reaction front and the spatial temperature and species profiles of the solid combustible, are obtained employing large activation energy asymptotics. It is found that the reaction fronts of both forward and opposed flows demonstrate unsteady behaviors for a higher thermal conductivity porous medium, a lower initial mass fraction of oxidizer and a lower gas flow velocity. The response of the moving speed of the reaction front of the forward mode to an increasing heat transfer coefficient is completely opposite to that of the opposed mode. In particular, the reaction front of the forward (opposed) flow becomes unsteady for lower (higher) heat transfer coefficient. However, for the middle ignition of a sample, the moving speed of the reaction front of the forward mode is found to monotonically increase with an increase of heat transfer coefficient, while in opposed mode it first increases and then decreases. The results also provide a remarkable finding that an "unsteady solution region" occurs in between the critical heat transfer coefficients of forward and opposed modes where the reaction fronts of both modes become unsteady. Moreover, the present solutions have been compared with previous numerical and experimental observations that show a qualitative agreement.

1. Introduction

One-dimensional propagation of a combustion wave is classified into two modes: forward and opposed. In forward mode, the combustion wave propagates in the same direction as the oxidizer flow while in opposed mode it propagates in the opposite direction of oxidizer flow. Ohlemiller [1] noted that the relative direction of oxidizer flow and the propagation of a combustion wave is a very important factor for the combustion of solid fuel which is rather unclear in many realistic configurations. Consequently, the forward and opposed modes have been the focus of research to date in the context of fire safety or from a technological point of view.

Purely forward and purely opposed mode are quite rare in fire safety problems, because the real-world fire-safety problems are deemed as coupled-forward and -opposed modes [2]. Yet, most of the studies in the field of fire safety (e.g., [3–9]) are focused on forward and opposed modes separately; while both of these modes are comparatively studied in [10–13]. The qualitative and quantitative differences between the two modes are identified experimentally in [11–13]. However, experiments have some limitations in their ability to investigate the responses of these modes to the important mechanisms of the process. Additionally, the focus of these past studies was to explore only the steady features, not the unsteady features, of the combustion wave.

On the other hand, there are some noticeable numerical studies [6–10] that mainly concentrated on finding the conditions of steady propagation of forward and opposed modes for the purpose of fire safety control. Among them, Rein et al. [10] only examined both modes under microgravity conditions that considered the heat loss but neglected the buoyancy effect. They found that the inclusion of heat loss to the exterior makes a significant difference in the combustion wave characteristics. But the model was solved numerically which is relatively time-consuming and difficult to be undertaken for a physical parameter. They even conceded that modifications in the ignition protocol significantly affect the results.

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Nomenclature

A	Pre-exponential factor [m^3 (kg s)$^{-1}$]
A_{sg}/V	Ratio of surface area between solid and gas to volume [m^{-1}]
a	Rosseland extinction coefficient [m^{-1}]
c_g	Specific heat capacity of the gas [J (kg K)$^{-1}$]
c_m	Specific heat capacity of the porous medium [J (kg K)$^{-1}$]
c	Ratio of heat capacities ($\equiv c_g/c_m$) [–]
D	Molecular mass diffusivity [m^2 s^{-1}]
D_{eff}	Effective diffusivity [m^2 s^{-1}]
D_K	Knudsen diffusion coefficient [m^2 s^{-1}]
d	Pore diameter [m]
E	Activation energy [J kg^{-1}]
h	Volumetric heat transfer coefficient from the porous medium to gas [W (m^3 K)$^{-1}$]
h_{ex}	Heat loss coefficient from the porous medium to the environment [W (m^3 K)$^{-1}$]
h_m	Mass transfer coefficient from the gas stream to the surface of fuel [m s^{-1}]
L	Length [m]
Le	Lewis number [–]
l	Ratio of thermal conductivities ($\equiv \lambda_g/\lambda_m$) [–]
M	Molar mass of gas [kg]
N_R	Radiation-conduction parameter [–]
Nu	Nusselt number [–]
n	Stoichiometric mass of oxygen per mass of fuel ratio [–]
Pr	Prandtl number [–]
Q	Fuel mass based heat of reaction [J kg^{-1}]
q_r	Radiative heat flux from the porous medium
R	Universal gas constant [J (kg K)$^{-1}$]
Re	Reynolds number [–]
r_f	Ratio of densities ($\equiv \rho_f/\rho_m$) [–]
r_g	Ratio of densities ($\equiv \rho_g/\rho_m$) [–]
S	Dimensionless temperature of the porous medium [–]
Sc	Schmidt number [–]
Sh	Interstitial mass transfer Sherwood number [–]
T	Temperature [K]
T_u	Ambient temperature [K]
t	Time [s]
u_g	Gas flow velocity [m s^{-1}]
u_f	Moving speed of the reaction front of forward mode [m s^{-1}]
u_s	Moving speed of the reaction front of opposed mode [m s^{-1}]
u	Ratio of gas flow velocity to reference velocity ($\equiv u_g/u_*$) [–]
x	Spatial distance [m]
Y	Volume-averaged mass fraction [–]
$Y_{F,u}$	Initial mass fraction of fuel [–]
$Y_{O,u}$	Initial mass fraction of oxidizer [–]
W	Rate of chemical reaction [kg (m^3 s)$^{-1}$]
w	Dimensionless rate of chemical reaction [–]

Greek symbols

α	Dimensionless heat of combustion [–]
β	Zel'dovich number [–]
Γ	Defined in Eq. (29)
Λ	Burning rate eigenvalue [–]
γ	Dimensionless heat release [–]
δ	Thermal excursion during the burning process [–]
ε	Porosity of the porous medium [–]
ζ	Dimensionless spatial coordinate [–]
θ	Dimensionless temperature of the gas [–]
κ	Thermal diffusivity of gas [m^2 s^{-1}]
λ	Thermal conductivity [W (m K)$^{-1}$]
Ω	Tortuosity factor [–]
Ω_{st}	Stoichiometric ratio ($Y_{F,u}/Y_{O,u}$) [–]
ν	Kinematic viscosity [m^2 s^{-1}]
ξ	Dimensionless spatial coordinate [–]
Π	Dimensionless constant [–] (Eq. (17))
ρ	Density [kg m^{-3}]
σ	Stefan-Boltzmann constant [W m^{-2} K^{-4}]

Subscripts

ad	Adiabatic value
F	Fuel
f	Fuel
g	Gas
ig	Ignition point
m	Porous medium
O	Oxidizer or Opposed
t	Derivative with respect to dimensionless time
$*$	Reference value

Superscripts

f	Value corresponding to forward mode
$\sim$	Dimensional value
$\wedge$	Dimensionless value

Apart from the fire safety context, the necessity of identifying the insights of different features of forward and opposed modes of the propagation of a combustion wave is also highly regarded in technological applications. Very recently, both forward and opposed modes have been recognized in the diesel particulate filter (DPF) regeneration process [14,15] by which solid particulate matters trapped in the porous channel walls of a DPF are burnt out at a steady state. Due to unknown aspects of the combustion of solid matters in the DPF, uncontrolled and unsteady combustion occurs during the DPF regeneration process. Consequently, the DPF may encounter a loss of its mechanical integrity and sometimes it undergoes complete collapse and so fails to trap particulate matters from the exhaust gas. Thus the regeneration process poses a major technological challenge. In this regard it has attracted much attention in order to reveal the unsteady conditions as well as the underlying insights into the combustion of solid particulate matters in the DPF.

Therefore, it is evident that both forward and opposed modes of a combustion wave are jointly observed in fire-safety problems and in technological applications; and the reasons for their steady and unsteady characteristics are not fully revealed to the scientific community. In particular, unsteady conditions need to be identified because most hazardous circumstances and technological problems are often brought about by the unsteady behaviors of the combustion wave. So the motivation for the comparative and combined study of forward and opposed modes is to provide the line of demarcation of the unsteady behaviors beyond which the combustion wave might demonstrate uncontrolled and unpredictable characteristics so that one can control a fire-hazard or protect a system from technological failure.

In this study, the universal model developed in [16] is used to study both forward and opposed modes combustion of solid fuel. To accomplish this goal, the governing equations formulated in [16] have been solved here for forward mode as well as for the middle ignition of a sample with appropriate boundary conditions. Large activation energy asymptotics is employed to obtain analytical expressions of the moving speed of the reaction front and the temperature and species profiles. The corresponding solutions of opposed mode are utilized here from [16]. Then, the effects of the thermal conductivity