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Combustion model of liquid fuel contained within an inert porous particle

Yoash Mor*, Alon Gany

Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

An analytical model describing the burning of a liquid fuel contained within an inert porous particle has been developed. It considers two heat transfer mechanisms: conduction and radiation. The solution of the problem is based on mass, species, and energy conservation as well as vapor–liquid equilibrium at the surface of the liquid fuel located at the core of the porous particle. The explicit solution predicts the main combustion parameters: flame temperature, flame radius, mass flow rate, liquid core radius, and fuel mass fraction at the liquid surface. These parameters exhibit different behavior than those of a burning liquid droplet (d^2 model). Nevertheless, the model reveals similar behavior of the profiles of the temperature and the mass fraction of the species.

1. Introduction

This paper presents a basic analytical model for the combustion process of a liquid fuel contained within a solid inert porous particle. The model may also be applied to the initial combustion stage of a combustible solid porous particle containing a volatile fuel of a much shorter combustion time scale. Certain high-energy-density systems may benefit from the use of porous high-density solid fuel particles loaded with a higher-energy liquid fuel. Such situations are not commonly encountered and hence are scarcely found in the literature.

Previous works on related subjects have been examined, e.g., combustion processes of a droplet [1–9], liquid fuel inside inert porous media [10], coal pyrolysis [11], and char combustion [12]. Though these works do not deal with the case considered here, one can utilize some of their basic assumptions, physical principles, and results. In particular, the works by Hayhurst and Nedderman [2] and Turns [1] have been helpful in the analytical modeling and physical approach of the present research.

As in the simplified d^2 model for a burning droplet [1,2], the present model assumes a quasi-steady-state, constant thermo-physical properties, binary diffusion, ideal gases, and Lewis number of unity. The model is based on four physical principles: mass conservation; species conservation in gas-phase regions (except at the flame sheet); energy conservation; and vapor–liquid equilibrium at the surface of the liquid core within the porous particle. This leads to six equations that predict the following combustion parameters: liquid core surface temperature, temperature at the surface of the solid particle, flame temperature, flame radius, fuel-vapor mass flow rate, and the mass fraction of fuel-vapor at the interface with the liquid core.

2. A physical description of the combustion model

An inert porous particle containing liquid fuel is surrounded by a concentric spherically symmetric flame zone and a quiescent, infinite medium of an oxidizer gas. The liquid fuel is gasified due to heat transfer from the flame. The fuel vapors diffuse radially outward and chemically react at the flame region with inwardly diffusing oxidizer.

The oxidizer may be air, oxygen or any other oxidizing gas mixture. Nevertheless, we assume binary diffusion and consider all other elements as inert, i.e., they influence the thermo-physical constants and the specific heat of combustion, but they do not participate in the chemical reaction.

Figure 1 illustrates the combustion region around the porous particle, marking the main parameters. The combustion process may be considered as a heat transfer and mass diffusion problem, which depends on the properties of the medium. Thus, the combustion region is divided into four zones (denoted by Roman numbers):

(a) *The Ist zone:* extends from infinity to the flame sheet (which is assumed to be infinitesimally thin). This zone contains only gases: oxidizer and combustion products. Heat is transferred by two mechanisms: conduction and radiation.

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* Corresponding author. Fax: +972 48295656.
E-mail addresses: yoashmor@gmail.com (Y. Mor), gany@tx.technion.ac.il (A. Gany).

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Nomenclature

A	Clausius–Clapeyron constant [Pa]
B	Clausius–Clapeyron constant [K]
c_p	specific heat [J/kg K]
D	mass diffusivity [m^2/s]
h_{fg}	latent heat of vaporization [J/kg]
Δh_c	heat of combustion [J/kg]
k	thermal conductivity [W/(m K)]
$\dot{m}$	mass flow rate [kg/s]
MW	molecular weight [kg/kmol]
P	pressure [Pa]
p	porosity
$\dot{Q}$	heat transfer rate [W]
R_0	universal gas constant = 8315 J/kmol K
r	radius [m]
T	temperature [K]
$\bar{T}$	average temperature [K]
v_r	bulk flow velocity [m/s]
χ	mass fraction
$Y_{F,l}$	fuel mass fraction at the droplet surface
α	thermal diffusivity [m^2/s]
ε	emissivity
ν	oxidizer to fuel stoichiometric ratio [kg/kg]
ρ	gaseous mean weight density [kg/m^3]
σ	Stefan–Boltzmann constant = 5.67×10^{-8} W/m^2 K^4

Subscripts

b	boiling
F	fuel
f	flame
g	gas
i	initial
l	liquid
lc	liquid core zone within the porous particle
ox	oxidizer
p	solid particle
pr	combustion products
r	radial direction
s	solid/solid particle
∞	infinity

(b) *The IInd zone:* The zone between the surface of the solid particle and the flame sheet. It includes only gases: fuel vapor and combustion products. Heat is transferred by two mechanisms: conduction and radiation.

(c) *The IIIrd zone:* The zone of the particle with empty pores; it includes the solid matrix frame (the porous particle) and fuel vapor. Heat is transferred by conduction through both phases – solid and gas.

(d) *The IVth zone:* The inner part of the particle with the liquid fuel core; it includes the heated liquid fuel and the solid matrix frame. This region may be modeled by one of two simple approaches: in-situ heat-up of the liquid bulk to a uniform temperature (namely, an initial stage where the liquid is heated uniformly up to about its boiling temperature and then undergoes steady evaporation), and the onion-skin model (according to which the droplet consists of two zones: an interior one with the initial temperature T_0 and a surface layer at T_l).

3. Assumptions

Similarly to the d^2 model (for a burning droplet), the present combustion model is based on the following assumptions:

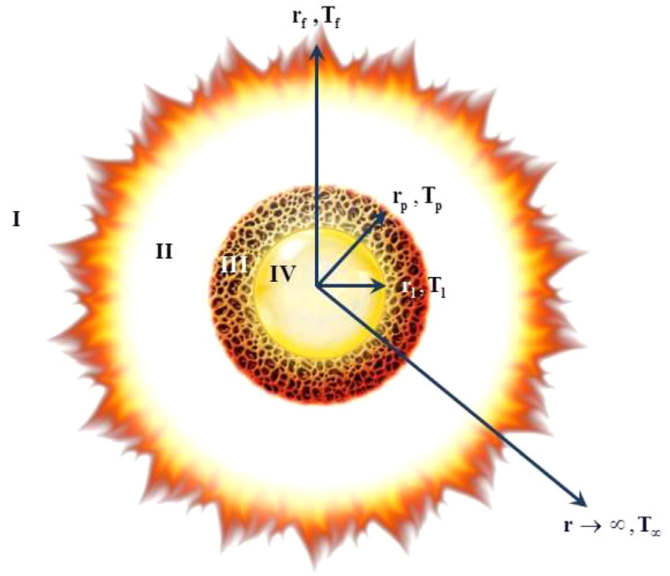

Fig. 1. A schematic illustration of the burning porous particle with important parameter marks on it. The Roman numbers denote the region division.

(a) The burning particle exists in a quiescent, infinite medium, without gravitation influence and with no interactions with adjacent droplets. Thus, the flame around the particle is spherically symmetric and the problem is one dimensional with radial symmetry.

(b) The chemical kinetics are assumed to be infinitely fast, forming a diffusion flame which can be represented as an infinitesimally thin sheet. In addition, we assume that fuel and oxidizer react at stoichiometric ratio at the flame zone and that all fuel vapors are consumed there.

(c) The particle has a uniform porosity, i.e. the ratio between the void and the solid areas at any radius is constant. Furthermore, the solid structure does not interrupt the diffusion of the gas; this assumption is valid for a highly permeable structure [10].

(d) The solid particle is inert and has a constant radius since it does not burn; only the evaporated liquid fuel does. Nevertheless, heat is conducted through the solid structure to the liquid fuel at the particle's core.

(e) Combustion is quasi-steady and the local temperatures of both the solid frame and the fuel vapor inside the void part of the particle are identical.

(f) The fuel is a pure (single-component) liquid with zero solubility for gases; it contains no other components such as soot or water. Phase equilibrium prevails at the liquid–vapor interface.

(g) The gas phase consists of only three "species": fuel vapor, oxidizer, and combustion products. The gas-phase region is divided into three zones as described above: zone IV contains oxidizer and combustion products, whereas zones II and III contain fuel vapor and combustion products. Thus, binary diffusion prevails in all parts of the gas-phase region.

(h) The “onion skin” model is used to describe the liquid core heating/evaporation regime.

(i) The pressure is uniform and constant.

(j) All thermo-physical properties of the gas components (thermal conductivity, specific heat, and ρD) are uniform (equal for all species), constant, and independent of temperature. Furthermore, thermal diffusivity and mass diffusivity are assumed to be equal (Lewis number is unity).