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A diffusion-flame analog of forward smolder waves: (I) 1-D steady structures

Zhanbin Lu^{a,b,*}^aInstitute of Applied Mathematics and Mechanics, Shanghai University, 149 Yan Chang Rd., Shanghai 200072, China^bShanghai Key Laboratory of Mechanics in Energy Engineering, Shanghai 200072, China

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ABSTRACT

A solid fuel may be viewed as a special kind of gas of vanishing molecular mobility. Accordingly, a forward smolder wave may be regarded as a special kind of diffusion flame with fuel Lewis number tending to infinity. Such a perspective is explored in this study to examine the structural characteristics of steady planar forward smolder waves, with particular emphasis placed on the heat loss effects. The problem is formulated by employing a diffusive-thermal model, in which the complex smolder reactions are modeled by a one-step exothermic char oxidation reaction. For both adiabatic and non-adiabatic cases, the reaction layer is analyzed by using the activation energy asymptotic method, which ends up with jump conditions connecting quantities across the reaction front. The asymptotic results indicate that adiabatic forward smolder waves do not have a blowoff limit in the small Damköhler number limit, whereas a quenching limit develops when heat loss effects are incorporated. For non-adiabatic forward smolder waves with a reaction trailing structure, the leakage of oxygen through the reaction layer vanishes to leading order, so the reaction zone is described by a structure that is essentially analogous to the premixed flame regime of diffusion flames. By contrast, in the presence of heat loss the reaction leading structure is characterized by $O(1)$ leakage of both reactants, so the analogy is with the partial burning regime of diffusion flames. The description of these two distinct structures, however, can be unified through a common dimensionless parameter m , which is defined as the fraction of heat conducted to the fresh solid fuel side among the total amount of heat generated in the reaction zone.

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1. Introduction

Smoldering refers to a kind of heterogeneous exothermic reaction taking place at the phase interface between a solid fuel and a gaseous oxidizer [1–5]. With continuous supply of the oxidizer, a smolder reaction front can be self-sustained and propagate toward the unburned solid in a wave fashion, hence also called a smolder wave. As a kind of surface reaction, the heat release rate of smoldering combustion is much smaller than that of flaming combustion, and the propagation velocity of smolder waves is in general several orders smaller than that of premixed flames.

From the practical perspective, smoldering is often the precursor of flaming combustion and thus constitutes a serious hazard to fire safety. On the other hand, as a fundamental combustion mode of solid fuels and liquid fuels in porous media as well, smoldering is involved in a wide variety of industrial technologies, such

as thermal oil recovery [6,7], coal gasification [8], high temperature synthesis (SHS) [9], soil contaminant remediation [10], waste incineration [11], and so on. Most of these technological applications involve the filtrational transport of an oxidizing gas through a porous medium, and therefore may be classified into the category of filtration combustion, or porous media combustion [12]. Another common configuration that involves smoldering combustion is the spread of a smolder front over a solid fuel layer, driven by an oxidizer flow sweeping over the fuel surface. Such a configuration has been exploited to realize the thermal-to-electrical energy conversion [13].

In order to investigate the fundamental structural characteristics of smolder waves, it is customary to define some basic one-dimensional configurations under forced flow conditions. According to the relationship between the directions of oxidizer flow and smolder front propagation, smolder waves are classified into two kinds, namely the reverse smolder wave if the smolder front propagates against the oxidizer flow, and the forward smolder wave if the smolder front propagates along the same direction as the oxidizer flow [14]. Structural characteristics of reverse smolder waves have been extensively studied in the literature by using

* Correspondence to: Institute of Applied Mathematics and Mechanics, Shanghai University, 149 Yan Chang Rd., Shanghai 200072, China.

E-mail addresses: zblu@i.shu.edu.cn, zblu@shu.edu.cn

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Nomenclature

Da	Damköhler number
Le	oxygen Lewis number
$\mathcal{D}$	scaled Damköhler number
B	pre-exponential factor
c_p	specific heat at constant pressure
D	mass diffusivity of oxygen
E	activation energy
f	volumetric heat loss
F'	function describing perturbed reaction surface
H	heat loss coefficient
h_1^+	excess enthalpy of oxygen
k	perturbation wave number
M	mass flux
m	fraction of heat conducted to fresh solid fuel side among total heat generated in reaction zone
n	spatial coordinate normal to reaction front
p	parameter arising from transformation of structure equation of non-adiabatic RTS
Q	heat of reaction per unit mass solid reactant
R	universal gas constant
r_ρ	gas-to-solid density ratio
S_L	left limiting function for non-adiabatic RTS
S_R	right limiting function for non-adiabatic RTS
T	temperature
t	time
V	smolder propagation velocity
X	oxygen mass fraction
x	spatial coordinate, or expansion of X in reaction layer
Y	fuel mass fraction
y	spatial coordinate, or expansion of Y in reaction layer

Greek symbols

α	factor appearing in canonical form structure equation of non-adiabatic RTS
δ	reduced Damköhler number
ϵ	small parameter characterizing amplitude of perturbation
η	independent variable of canonical form structure equation of non-adiabatic RTS
γ	fraction of fuel consumed by reaction among total fuel convected to reaction zone
Λ	parameter characterizing 1-D steady solution of adiabatic RTS
λ	heat conductivity
μ	stoichiometric coefficient of oxygen
Ω	reaction rate
ρ	density
σ	perturbation growth rate
τ	expansion of T in reaction layer
θ	dimensionless activation temperature
ε	small parameter inversely proportional to activation energy
φ	dependent variable of canonical form structure equation of non-adiabatic RTS
ξ	stretched variable in reaction layer
ζ	spatial coordinate tangential to reaction front

Subscripts and superscripts

*	value at reaction front
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∞	condition corresponding to infinite Damköhler number
a	value corresponding to adiabatic condition
b	value corresponding to non-adiabatic condition
cr	value under critical condition
eff	effective value
f	ambient or fresh supply condition
g	gas
max	maximum value
M	value under marginal condition
N	value under neutral condition
q	value at quenching limit
r	reference value
st	stoichiometric condition
s	solid
$\pm$	immediately downstream (+) or upstream (-) of reaction front
'	perturbation quantity

Abbreviations

FCI	fingering or cellular instability
RTS	reaction trailing structure
RLS	reaction leading structure
TWI	traveling wave instability

Other symbols

$[[()]]$	jump across reaction front
$\bar{()}$	1-D steady solution
$()$	dimensional form of variable or parameter

experimental [14–16], analytical [17–20] and numerical [21–23] approaches. The focus of the present study is the forward configuration of smoldering combustion.

One primary difference between reverse and forward smolder waves lies in the modeling of the chemical reaction pathways. For the reverse configuration, the pyrolysis of the virgin solid fuel and the subsequent char oxidation reaction proceed almost simultaneously and thus may be modeled as a lumped combustion reaction. By contrast, for the forward configuration, the hot gaseous products that pass through the reaction zone may significantly heat up the virgin solid fuel, leading to a separate pyrolysis front that advances ahead of the char oxidation front. Dosanjh and Pagni [24] analyzed the structure of planar forward smolder waves by considering such a two-step chemical reaction model, along with the assumptions of fixed pyrolysis temperature and infinite oxidation kinetics. Their analysis was furthered by Buckmaster and Lozinski [25], who examined the oxidation zone structure through a rigorous asymptotic analysis, and discussed the late-time solution properties of unsteady forward smolder waves.

Schult et al. [26] carried out a comprehensive asymptotic analysis of the structure of adiabatic forward smolder waves by neglecting the pyrolysis process and retaining only the char oxidation reaction. Their analysis showed that an adiabatic forward smolder wave is characterized by a structure that consists of two layers, namely a heat transfer layer and an oxidation reaction layer, each propagating along the same direction at a constant yet different velocity. According to the relative positions between these two layers, forward smolder waves can be classified into two different kinds of structures, namely the reaction trailing structure if the oxidation reaction layer trails behind the heat transfer layer, and the reaction leading structure if the oxidation reaction layer leads the heat transfer layer. The reaction trailing and reaction leading regimes are separated by a singular, or resonant regime, which is characterized by an accumulation of the thermal energy within the oxidation reaction front [27]. The asymptotic analysis of Schult

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