



Analytical solutions of superadiabatic filtration combustion

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ABSTRACT

Analytical solutions for superadiabatic filtration combustion of lean methane-air mixtures in a monolithic porous burner are sought. The one-dimensional, local volume-averaged equations of energy and species conservation that assume a non-thermal equilibrium (i.e., the two-medium treatment), are converted by a coordinate transformation using a combustion wave speed and solved to obtain close-form solutions. A parametric examination varying inlet gas velocity, fuel equivalence ratio, porosity, and thermal conductivity and diffusivity of the solid phase of the porous burner proves the validity of the analytical solutions which are in an excellent agreement with the numerical benchmark. The analytical solutions depict the key features of the filtration combustion such as non-thermal equilibrium between the solid and gas phases, superadiabatic flame temperature, and internal heat recirculation between solid and gas phases of the porous burner.

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1. Introduction

Filtration combustion in monolithic porous burners is much of interest because of its unique characteristics of moving reaction front, interphase heat exchange, heat recirculation, lean combustion, and superadiabatic flame temperature. Because of rising fuel cost, it is essential to recover unused thermal energy in combustion products for improvement of the combustion process and increase of the energy efficiency of combustors. The heat recovery in the porous burners is typically made by a heat recirculation from hot combustion products to cold combustion reactants through interphase heat exchange between gas flows and solid matrix of the porous burners, which has been widely used in power generation and propulsion systems. Weinberg pioneered the heat recirculation concept to achieve an excess enthalpy combustion [1]. Because of the temperature limitation (melting points) of combustor materials, low-temperature combustion seems to be a rational choice employing a lean combustion possible by the heat recirculation [1–8].

The idea of the excess enthalpy combustion has been explored by many researchers [2,9–14]. A simple way to achieve the excess enthalpy combustion uses a solid matrix (porous material) of high thermal conductivity in a combustor such that the combustion

heat is internally recirculated from hot exhaust gas to cold combustion reactants by the conduction and radiation through the solid matrix. The premixed combustion in the porous burner can be analyzed using either a one-temperature model based on a thermal equilibrium between the gas and solid phases [15] or a two-temperature model [10,12,16–20] assuming a non-thermal equilibrium between the phases [5,21–26]. Takeno et al. [12] presented theoretical results on the excess enthalpy combustion considering a non-thermal equilibrium between the phases and assuming constant solid-phase temperature. They showed the existence of a critical gas flow rate above which a combustor can't sustain its combustion.

The superadiabatic combustion in porous media using a reciprocating flow has also been extensively studied by Hanamura and Echigo [11] and Park and Kaviany [27] using two-temperature models. Hanamura and Echigo reported from their analysis using high Peclet number conditions that the maximum flame temperature could be 13 times higher than the theoretical temperature because of the internal heat recirculation [11]. The superadiabatic combustion in a two-section porous burner using embedded radiation corridors and an external preheater was studied numerically by Vandadi et al. [5,21,22,28]. They predicted a radiant burner efficiency over 45% which is possible by dual (internal and external) heat recirculation.

In this paper, analytical solutions of filtration combustion in a one-dimensional monolithic (homogeneous) porous burner are presented. A two-temperature model [29] assuming a local non-thermal equilibrium was used to formulate the governing

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Nomenclature

Ai	Airy function	γ	coefficient
a	pre-exponential factor of combustion reaction [1/s]	Δ	thickness [m] or difference
Bi	Airy function	Δh_c	standard heat of combustion reaction [J/kg]
C	coefficient	ε	porosity
c	specific heat [J/kg K]	η	non-dimensional fuel concentration
D	species diffusivity [m ² /s] or coefficient	θ	non-dimensional temperature
d_p	pore diameter [m]	μ	viscosity [Pa s]
E	activation energy [J/kmol]	ρ	density [kg/m ³]
F	function	φ	equivalence ratio, $(\rho_{F,g}/\rho_g)/(\rho_{F,g}/\rho_g)_{stoich}$
h_v	volumetric interstitial heat transfer coefficient [W/m ³ K]		
k	thermal conductivity [W/m K]	Subscripts	
Le	Lewis number, $[k_g/(\rho c_p)_g]/D$	ad	adiabatic
M	coefficient	b	baseline
N	coefficient	c	combustion
Nu	Nusselt number, $h_v d_p^2/k_g$	F	fuel
Pe	Peclet number, $\rho_g c_p u_{in} d_p/k_g$	f	flame
Pr	Prandtl number	g	gas phase
Re	Reynolds number, $\rho_g u_{in} d_p/\mu$	I	preheating zone
R	universal gas constant [J/kmol K]	II	combustion zone
T	temperature [K]	ig	ignition
S	non-dimensional variable	in	inlet
t	time [s]	max	maximum
u	velocity in x direction [m/s]	min	minimum
v	velocity of moving flame [m/s]	p	pore or pressure
W	rate of consumption of fuel [kg/m ³ s]	s	solid phase
x	coordinate [m]	$stoich$	stoichiometric
Y	mass fraction of species, ρ/ρ_g	v	volumetric
Ze_{ig}	Zeldovich number, $E(T_{ad} - T_{ig})/RT_{ig}^2$		
z	non-dimensional coordinate	Superscripts	
		*	non-dimensional
Greek letters		'	shifted coordinate
α	thermal diffusivity [m ² /s]		
β	coefficient		

equations. The governing equations were converted by a coordinate transformation using a combustion wave speed. The analytical solutions of the energy conservation for solid and gas phases and the fuel conservation are sought considering all the heat transfer terms such as advection, convection, conduction, diffusion and combustion reaction.

2. Governing equations

The premixed combustion in a monolithic porous burner is called filtration combustion because the flame moves along the flow direction in the burner and consequently the temperature and concentration profiles vary with time. The equation of energy conservation of the solid phase in the burner is given by

$$c_s \rho_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x} \left(k_s \frac{\partial T_s}{\partial x} \right) + \frac{h_v}{1 - \varepsilon} (T_g - T_s) \quad (1)$$

where ε is porosity and h_v is a volumetric, interstitial heat transfer coefficient $h_v = (k_g/d_p^2)0.683Re^{0.42}$ [5]. It is also assumed that the surface emissivity of the solid phase of the porous medium in the burner is very low that the threshold value of the radiant conductivity introduced by Kaviany and Singh [30] is negligible.

The equation of energy conservation of the gas phase is given by

$$c_g \rho_g \frac{\partial T_g}{\partial t} + c_g \rho_g u \frac{\partial T_g}{\partial x} = \frac{\partial}{\partial x} \left(k_g \frac{\partial T_g}{\partial x} \right) + \frac{h_v}{\varepsilon} (T_s - T_g) + \Delta h_c \rho_g W(Y_F, T_g) \quad (2)$$

where the first-order Arrhenius-type reaction $W(Y_F, T_g) = aY_F \exp(-E/RT_g)$ is used. Note that the interstitial heat exchange between the solid and gas phases couples the energy equations.

The equations of mass conservation for the fuel species and gas flows are given by

$$\rho_g \frac{\partial Y_F}{\partial t} + \rho_g u \frac{\partial Y_F}{\partial x} = \frac{\partial}{\partial x} \left(\rho_g D \frac{\partial Y_F}{\partial x} \right) + \rho_g W(Y_F, T_g) \quad (3)$$

$$\frac{\partial \rho_g}{\partial t} + \frac{\partial \rho_g u}{\partial x} = 0 \quad (4)$$

2.1. Non-dimensional equations

The filtration combustion in a monolithic porous burner is inherently a dynamic (transient) problem characterized by a moving combustion wave front (sweeping flame). Assuming an infinitely long one-dimensional porous material and noting that the flame moves at a constant combustion wave speed, the entire conservation equations become shift invariant. The conservation equations of the moving flame may then be transformed to the form of a standing flame by introducing the combustion wave speed (v) which allows an easier analysis of the problem. The new set of equations still retains the transient characteristic of the problem which is presented in the form of spatial derivatives.

The set of conservation equations is rewritten in a non-dimensional form. By introducing a new coordinate variable, $x' = x - vt$ and using non-dimensional variables below

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