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The influence of radiation on the flame propagation through micro organic dust particles with non-unity Lewis number

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In this paper, the analytical study of effects of radiation and non-unity Lewis number on the laminar premixed flames of organic dust clouds has been done. The research is focused on a combustion model for premixed flames and the flame structure is composed of preheat-vaporization, narrow reaction and finally the post-flame zone. The normalized governing equations with help of boundary and matching conditions are solved by perturbation method. The results show that increasing equivalence ratio and decreasing Lewis number are resulted in the increase of flame temperature and burning velocity. For the sake of this model validation, fuel conversion is compared by published experimental data and shows an acceptable agreement.

1. Introduction

Knowledge of organic dust particles combustion for its importance in science and engineering need to be improved and developed both in experimental and theoretical approach.

Combustion of cloud particles due to complexity of its mechanism is relatively underdeveloped in comparison with homogenous combustion. Thus, it is necessary to utilize a model which can be simple and readily verified. The theory of the flame propagation in the uniformly dispersed, quiescent, gravity free, particle clouds has been developing for decades [1–3]. Many aspects of these theoretical models closely parallel those for premixed gaseous systems. Uniform dispersion of particulates is generally assumed in these models. In relevance to the combustion of particle dust cloud, a two-dimensional analytical model of micro-sized aluminum dust cloud combustion in a channel has developed by Bidabadi et al. [4] with the assumption of a laminar, steady-state and uniform flow and with the purpose of gaining flame speed, quenching distance, lean flammability limit, and temperature distribution.

One of the important parameters in the combustion of the organic dust particle is to determine the incredible impact of Lewis number on the combustion characteristics of dust particle. Therefore in the following part, the conducted researches associating with the organic dust combustion and the effect of Lewis number are categorized.

Han et al. [5,6] observed some downward propagating flames in the Lycopodium particle behind the upward propagating flame. Also the flame thickness in a Lycopodium dust flame is observed to be 20 mm, about several orders of magnitude higher than that of a premixed gaseous flame and from the microscopic visualization, it was found that the flame front propagating through the Lycopodium particles is discontinuous and not smooth.

Kurdyumov and Tarrazo [7] numerically investigated the propagation of premixed laminar flames with different Lewis numbers in open ducts of circular cross-section in a thermal-diffusive model. He explored that when the Lewis number is less than unity the flame velocities in ducts with an isothermal wall may exceed those in ducts with an adiabatic wall of the same diameter, because of the appearance of cellular structures, which increase the curvature effect triggered by the boundary conditions at the wall.

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Nomenclature

a	defined in Eq. (31)
A	parameter characterizing rate of vaporization of fuel particles
b	scaled mass fraction of fuel at the boundary between the reaction and convection zones
B	frequency factor characterizing rate of gas phase oxidation of the gaseous fuel
B'	defined in Eq. (21)
D_u	diffusion coefficient
E_a	activation energy characterizing the gas phase reaction
I_f	radiation intensity from the flame to preheat zone
k	rate constant of the gas-phase reaction
k_a	absorption coefficient
k_s	scattering coefficient
k_t	defined in Eq. (11)
Le	lewis number, defined in Eq. (20)
m	defined in Eq. (15)
n	temperature exponent characterizing rate of vaporization of fuel particles, Eq. (1)
n_s	local number density of particles
n_u	number density of particles in ambient reactant stream (number of particles per unit volume)
q	defined in Eq. (20)
Q	heat release per unit mass of gaseous fuel consumed
Q_a	absorption heat
Q_s	scattering heat
Q_r	radiation heat transfer between reaction and preheat-vaporization zones
Q_V	heat associated with vaporizing unit mass of fuel
r	radius of fuel particle
R	gas constant
t	defined in Eq. (41)
T	temperature
v	velocity
v_v	including heat burning velocity calculated
v_u	neglecting heat burning velocity calculated
ω_v	rate of vaporization of fuel particles, Eq. (1)
υ	stoichiometric coefficient
ϕ_g	effective equivalence ratio in the reaction zone
ϕ_u	equivalence ratio based on fuel available in the particles in the ambient reactant stream

Subscripts

b	adiabatic conditions after completion of chemical reactions

C	heat capacity of mixture
C_F	molar concentration of fuel
C_p	heat capacity of the gas
C_s	heat capacity of a fuel particle
C'	defined in eq. 22
d_p	diameter of the particle
W_F	molecular weight of gaseous fuel
x	independent variable coordinate that is made in length of flame speed
x'	spatial coordinate
y	defined in Eq. (41)
y_F	defined in Eq. (15)
y_s	defined in Eq. (15)
Y	mass fraction
Y_FC	defined in Eq. (16)
Y_Ff	mass fraction of fuel at the reaction zone
Y_Fu	gaseous fuel available in the particles in the ambient reactant stream
z	scaled independent variable, Eq. (15)
Ze	defined in Eq. (2)

Greek symbols

α	defined in Eq. (28)
γ	defined in Eq. (20)
ε	$1/Ze$, expansion parameter
η	independent variable defined in Eq. (41)
θ	scaled independent variable, Eq. (15)
θ^0	value of θ calculated neglecting heat of vaporization of particles
Λ	defined in Eq. (47)
λ	thermal conductivity
ρ	density of the reactant mixture
ρ_p	density of the particle
ω	defined in Eq. (45)
ω_F	reaction rate characterizing consumption of gaseous fuel, Eq. (39)
F	gaseous fuel
f	conditions at the reaction zone
$\mathrm{O_2}$	oxygen
prod	production of chemical reaction
s	fuel particles
u	conditions in the ambient reactant stream

Proust [8,9] measured the laminar burning velocities and maximum flame temperatures for combustible dust-air mixtures such as starch dust-air mixtures, Lycopodium–air mixtures and sulfur flour–air mixtures.

Eckhoff [10] clarified the differences and similarities between dust and gases and it was found that there are two basic differences between dusts and gases which are of substantially greater significance in design of safety standards than these similarities. Firstly, the physics of generation and up-keeping of dust clouds and premixed gas/vapour clouds are substantially different. Secondly, contrary to the premixed gas flame propagation, the propagation of flames in dust/air mixtures is not limited to the flammable dust concentration range of dynamic clouds.

Chakraborty et al. [11] presented a thermo-diffusive model to investigate the interaction of non-unity Lewis number and heat loss for laminar premixed flames propagating in a channel. A coordinate system moving with the flame was used to immobilize the flame within the computational domain.

The other parameter which plays an important role in the organic dust combustion phenomenon is the influence of radiation heat transfer and associating with this effect, according to the radiation effect, Datta and Saha accomplished a numerical study to understand the contribution of self-absorption and soot radiation in a laminar methane-air diffusion flame [12]. A gray radiation model was applied using the first-order moment method to evaluate the emission and absorption of radiation.