Fuel Processing Technology 179 (2018) 184–196

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Theoretical study of non-adiabatic counter-flow diffusion flames propagating through a volatile biomass fuel taking into account drying and vaporization processes

Mehdi Bidabadi, Saman Hosseinzadeh, Mostafa Setareh, Pedram Panahifar, Sadegh Sadeghi*

School of Engineering, Mechanical Engineering Department, Iran University of Science and Technology, Narmak, Tehran, Iran

ARTICLE INFO

Keywords:
Diffusion flame
Non-adiabatic combustion
Biomass fuel
Asymptotic method
Counter-flow configuration

ABSTRACT

Due to important advantageous of non-premixed flames such as controllability and safety, a proper investigation can be highly beneficial for application of these flames in medical and power generation industries. The current paper attempts to provide a promising analytical model for non-adiabatic counter-flow diffusion flames propagating through volatile biomass particles using an asymptotic method. In order to offer a reliable model for analysis of the flames, a multi-zone flame structure including preheat, drying, vaporization, reaction and oxidizer zones, is considered. In this work, lycopodium particles and air are taken as biofuel and oxidizer, respectively. For following the influences of effective dimensionless numbers, such as fuel and oxidizer Lewis numbers on the flame structure, dimensionalized and non-dimensionalized forms of mass and energy conservation equations are derived for each zone. In order to observe the heat loss effects, a linear term is added to the energy conservation equation. The conservation equations are solved by Mathematica and Matlab software applying accurate boundary and jump conditions. Finally, variations of flame temperature, flame front position, gaseous fuel and oxidizer mass fractions with fuel and oxidizer Lewis numbers, mass particle concentration, particle size, equivalence ratio and heat loss effect are elaborately elucidated.

1. Introduction

Due to the finite reserves of fossil fuels and their adverse impacts on the environment, organic resources as an alternative fuel have recently attracted much attention among the scholars seeking promising environmentally-friendly combustion processes [1–3]. Flames produced by combustion of organic dust particles can be classified into premixed, partially premixed and non-premixed (diffusion) flames [4]. As oxidizer and fuel are separated before reaching the reaction zone in non-premixed flames, these flames are more controllable and safer [5, 6]. Because of these significant characteristics, diffusion flames have extensively been applied in various industries such as gas turbine engines, coal furnaces and diesel internal combustion engines [7]. So far, numerous studies have been conducted to predict the behavior of flames, particularly premixed flames, under different circumstances. Bidabadi et al. used a mathematical method to model the structure of premixed flames propagating through the mixture of organic dust particle and air in a counter-flow configuration considering preheat, vaporization, reaction and post-flame zones [8]. Haghiri and Bidabadi [9] suggested an analytical model for multi-zone premixed flames propagating through the mixture of organic fuel particles and air considering thermal radiation effects [9]. Kitajima et al. [10] experimentally described the structure and extinction of turbulent non-premixed flames in counter-flow configuration. Liu et al. [11] used an asymptotic method of large activation energy to investigate the radiative extinction in counter-flow diffusion flames assuming non-unity Lewis numbers. Smooke et al. [12] numerically and experimentally studied the structure of a counter-flow diffusion flame burning diluted methane in diluted air. Han et al. [13] experimentally examined the behavior of premixed flames moving upward through lycopodium dust clouds taking into account the gravitational effects. Amantini et al. [14] employed computational and experimental approaches to evaluate the behavior of steady counter-flow non-premixed flames burning methane fuel. Bidabadi et al. [15] proposed an analytical model to study the propagation of premixed flames burning moisty lycopodium particles considering preheat, drying, vaporization, reaction and post-flame zones. Short and Liu [16] measured oscillations in counter-flow non-premixed edge-flames for unit Lewis numbers. Bidabadi et al. [17] studied the effect of significant parameters on the initiation of instability in premixed flames taking into account thermal radiation effects. Bak et al. [18] numerically

---

* Corresponding author.
E-mail address: sadeghsadeghi@mecheng.iust.ac.ir (S. Sadeghi).

https://doi.org/10.1016/j.fuproc.2018.07.005
Received 24 April 2018; Received in revised form 6 July 2018; Accepted 7 July 2018

Nomenclature

a	Flow strain rate
B	Frequency factor
C	Specific heat capacity of mixture
C_a	Specific heat capacity of gas
C_S	Specific heat capacity of solid fuel particles
D_C	Damkohler number
D_F	Diffusion coefficient of gaseous fuel
D_O	Diffusion coefficient of oxidizer
D_T	Heat conduction coefficient
E	Overall activation energy
F	Gaseous fuel
Le_F	Fuel Lewis number
Le_O	Oxidizer Lewis number
m	Molecular weight of mixture
m_f	Molecular weight of fuel
m_O	Molecular weight of oxidizer
n_S	Density number of particles per unit volume
Q	Heat released by combustion of reactants
Q_{dry}	Latent heat of drying
Q_{vap}	Latent heat of vaporization heat of drying to the heat released from reaction
q_{dry}	Ratio of latent heat of drying to the heat released by combustion
q_{vap}	Ratio of latent heat of vaporization to the heat released by combustion
r_P	Radius of solid particles
S	Solid fuel
T_a	Activation temperature
T_{dry}	Drying temperature of dust particles
T_{vap}	Vaporization temperature of dust particles
T_f	Flame temperature
T_∞	Ambient temperature
x_{dry}	onset position of drying
x_f	flame position
x_{vap}	onset position of vaporization
y_F	Dimensionless mass fraction of gaseous fuel
y_O	Dimensionless mass fraction of oxidizer
y_S	Dimensionless mass fraction of solid fuel
$Y_{F-\infty}$	Mass fraction of fuel in gaseous phase at $X = -\infty$
Y_S	Mass fraction of fuel in solid phase
Y_O	Mass fraction of the oxidizer
Y_F	Mass fraction of gaseous fuel
Z	Secondary coordinate axis

Greek symbols

$\boldsymbol{\alpha}$	Oxidizer initial mass fraction
ω_{dry}	Drying rate of a particle
ω_F	Rate of the chemical-kinetic
ω_{vap}	Vaporization rate of a particle
τ_{dry}	Constant characteristic time of drying
τ_{vap}	Constant characteristic time of vaporization
λ	Thermal conductivity of fuel or oxidizer
$\varnothing_u$	Equivalence ratio of the volatile fuel
ρ	The density of the reactant mixture
ρ_S	Dust particle density
ρ_a	Density of gas
ϑ	Stoichiometric mass ratio of oxidizer to fuel
θ	Dimensionless temperature
θ_{dry}	Dimensionless form of drying temperature
θ_f	Dimensionless form of flame temperature
θ_{vap}	Dimensionless form of vaporization temperature
ϑ_O	Number of oxygen's moles reacting with one mole of fuel
Le	Lewis number
λ	Thermal conductivity of fuel or oxidizer
ν	Stoichiometric coefficient
κ	Heat transfer coefficient

Subscripts

a	Gas
F	Fuel
H	Heaviside
P	Product
R	Universal gas constant
u	Velocity in Y direction
v	Velocity in X direction
vap	Vaporization
dry	Drying
f	Flame
Ze	Zeldovich number

investigated the instabilities leading to extinction of non-premixed tubular flames. Bidabadi et al. [19] conducted a mathematical investigation to analyze the structure of non-premixed burning organic dust flames in counter-flow configuration. Proust [20] studied the structure and propagation of laminar premixed flames through several combustible mixtures. Seshadri and Trevino [21] reported the effect of Lewis number on the structure of counter-flow diffusion flames using an asymptotic method. Seshadri et al. [22] modeled the structure of premixed flames fed with volatile fuel particles in an oxidizing gas mixture. Bundy et al. [23] experimentally examined the suppression of low-strain-rate counter-flow non-premixed flames considering minimal conductive heat losses. Linan [24] employed an asymptotic method to describe the structure of counter-flow diffusion flames taking into account large quantities of activation energy. Rahbari et al. [25] theoretically studied the behavior of lycopodium particles in premixed combustion mode considering thermophoretic, gravitational and buoyancy forces. Bidabadi et al. [26] analytically presented the effect of radiation and particle size on pyrolysis (thermal decomposition) of wood particles burning during premixed combustion. Daou et al. [27] developed a thermo-diffusive model to investigate the impact of heat loss on shape of the generated flame in counter-flow non-premixed combustion. Bidabadi and Rahbari [28] presented the influence of temperature difference between lycopodium fuel particles and oxidizing gas on the behavior of premixed flames. Bidabadi et al. [29] analytically predicted the effects of thermal radiation and heat loss on the structure of non-adiabatic premixed flames. Oh et al. [30] experimentally and numerically perused the impact of fuel composition on stabilization and luminescence of non-premixed flames. Dinesh et al. [31] used large eddy simulation (LES) technique to clarify the dynamic behavior of four turbulent non-premixed flames. Safer et al. [32] numerically simulated the structure of a syngas counter-flow non-premixed flame considering NO emissions and strain rate. As reviewed in the literature, although vast number of numerical and experimental studies have been undertaken to model the structure of flames under different conditions, very few mathematical investigations have been conducted to predict the behavior of multi-zone non-adiabatic diffusion flames propagating through mixture of organic volatile fuel and oxidizing gas in counter-flow configuration. Since heat losses can have remarkable effects on the flame extinction and structure, a reliable study for analysis of flames characteristics under non-adiabatic conditions is required. In this study, for the first time, an analytical model is suggested for non-adiabatic counter-flow diffusion flames fueled by volatile biomass particles. To