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Numerical investigation of biogas flameless combustion

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ABSTRACT

The purpose of this investigation is to analyze combustion characteristics of biogas flameless mode based on clean technology development strategies. A three dimensional (3D) computational fluid dynamic (CFD) study has been performed to illustrate various priorities of biogas flameless combustion compared to the conventional mode. The effects of preheated temperature and wall temperature, reaction zone and pollutant formation are observed and the impacts of combustion and turbulence models on numerical results are discussed. Although preheated conventional combustion could be effective in terms of fuel consumption reduction, NO_x formation increases. It has been found that biogas is not eligible to be applied in furnace heat up due to its low calorific value (LCV) and it is necessary to utilize a high calorific value fuel to preheat the furnace. The required enthalpy for biogas auto-ignition temperature is supplied by enthalpy of preheated oxidizer. In biogas flameless combustion, the mean temperature of the furnace is lower than traditional combustion throughout the chamber. Compared to the biogas flameless combustion with uniform temperature, very high and fluctuated temperatures are recorded in conventional combustion. Since high entropy generation intensifies irreversibility, exergy loss is higher in biogas conventional combustion compared to the biogas flameless regime. Entropy generation minimization in flameless mode is attributed to the uniform temperature inside the chamber.

1. Introduction

Industrial development is in debt of energy consumption and more than 80% of the world energy demand is supplied by different kinds of fossil fuels. However, the resources of fossil fuels are depleted day by day and the future energy scenario of the world has become one of the main concerns. Indeed, environmental concerns have increased due to raising rate of emissions released from fossil fuel combustion. Global warming (GW) has become one of the most important environmental issues due to increasing rate of greenhouse gases (GHGs) generation. Therefore, the request for clean alternative fuel and efficient combustion technology has become more important [1–3]. In recent decades, utilization of renewable and sustainable energy such as biomass, solar energy, wind energy, hydropower and geothermal has been developed properly. Furthermore, biogas from wastewater effluent, municipal solid wastes (MSW), animal waste and agricultural by-products have been employed for combined heat and power (CHP) generation purposes [4–8]. In the other hand, necessity of biogas collection from aforementioned resources is unavoidable because CH_4 and CO_2 as the main components of biogas participate in the GW constitution actively [9]. Since the negative effect of CH_4 on the GW is 23 times more than CO_2, biogas collection from anaerobic digestion (AD) has become more highlighted. In most of the AD, the percentage of CH_4 is enough to be considered as a clean fuel. The amount of CH_4 in biogas components depends on the feedstock is various (from 40% up to 60%) [10]. In biogas conventional combustion, pollutant formation mitigates compared to traditional combustion of pure CH_4. However, biogas traditional combustion encounters some problems due to LCV of biogas. Therefore, biogas should be upgraded to remove its non-combustible CO_2 impurity [11]. Based on the application of biogas, pure biogas can be cleaned and upgraded by some technologies such as water scrubbing, cryogenic process and membrane. In order to prevent implementation of upgrading equipment, application of flameless combustion was proposed for pure biogas combustion. Since combustion is still the most important technique for energy generation, flameless combustion was introduced to improve the combustion efficiency and decrease pollutant formation concomitantly [12,13]. The importance of flameless combustion technology has become more highlighted when the inability of other combustion technologies in terms of simultaneous pollutant reduction and thermal efficiency enhancement was proven. Low emission formation in flameless combustion is obtained due to dilution of the air combustion by inert gases such as nitrogen (N_2) and CO_2 [14–16]. Therefore,

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Nomenclature

$\vec{r}$	position vector	$T_{s,o}$	outer surface temperature
$\vec{s}$	direction vector	T_∞	the ambient temperature set at 300°K
I	radiation intensity	h	natural convection coefficient
I_λ	radiation intensity for wavelength λ	σ	Stephane-Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
a_λ	spectral absorption coefficient	ε	solid surface emissivity
$I_{b\lambda}$	black body intensity	x	percentage of excess air
$\vec{s}'$	scattering direction vector	β	mole fraction of CO_2 in biogas
s	path length	r	density (Kg/m^3)
n	refractive index	k_f	thermal conductivity of fluid
σ_s	scattering coefficient	Y_i	mass fraction of species i
σ	Stephan-Boltzmann constant (5.669×10^{-8} W/m^2 K^4)	W_i	generation or consumption of specious
Φ	phase function		
Ω'	solid angle		

combustion instability can be appeared due to low amounts of oxidizer and consequently flame quenching occurs. Thus the high temperature of diluted oxidizer plays an important role to exceed the auto – ignition temperature of the fuel. It can be construed that required enthalpy is supplied by preheating the oxidizer to achieve the self-ignition temperature of the fuel [17]. Although the great performance of flameless combustion has been developed in terms of fossil fuel utilization, various aspects of biogas flameless combustion have not been investigated properly. Since computational analyses are becoming more important due to their acceptable accuracy and lower cost, different perspectives of biogas flameless combustion can be analyzed numerically. The theoretical study using CFD software decreases errors and trials on experimental investigations for development of new models. In this article, a CFD modeling of biogas flameless combustion is investigated to identify the most important parameters that should be considered in biogas flameless regime. The effects of chemical kinetic mechanisms, turbulence models, radiation heat transfer and differential diffusion effects on the accuracy of the model are noted.

2. Conventional combustion of LCV fuels

One of the most important barriers for biogas utilization development is its low calorific value as well as its corrosive nature. LCV fuels were not taken into account in the energy mix of the world due to the abundance of high calorific value fossil fuels and lower energy prices in the past. However, recent enhancements of energy prices and concerns of the future energy scenario have attracted more attention to LCV fuel utilization in power generation. Therefore, combustion characteristics of various combinations of biogas have become more important. It has been claimed that raw biogas cannot be utilized in commercial burners directly as the substitution of natural gas (NG) or liquid petroleum gas (LPG). If biogas conducted to the traditional burner orifice at the pressure intended for charging NG or LPG, the air fuel ratio is not sufficient for combustion stability due to high CO_2 content of biogas. Thus, a new burner with the separate control measurement system should be installed for biogas. Since water vapor and H_2S as the components of biogas have corrosive characteristics, the condensation should be prevented by maintaining the furnace temperatures above the dew point temperature. It means that the combustion furnace should be heated up by NG or LPG to obtain higher operating temperature [18]. Therefore, a dual role burner should be installed in conventional combustion system fueled by biogas. Indeed, in order to switch over from NG or LPG to biogas some equipment should be employed. Consequently, complicated setting and the low efficiency of the conventional combustion systems can encourage biogas users to apply flameless combustion in their combustion process [19].

3. Numerical studies of flameless regime

Flameless combustion has been referred as flameless oxidation, colorless distributed combustion, moderate or intense low oxygen dilution (MILD) combustion and high-temperature air combustion (HiTac) [20]. In the flameless mode, combustion takes place in a distributed reaction zone with uniform low temperature. The fluctuations of temperature are omitted in flameless regime compared to the conventional flames. Combustion occurs in a low oxygen concentration atmosphere without visible flame. Indeed, the levels of the noise, NO_x and soot emissions decrease [21]. Due to complicated conditions in flameless mode, numerical modeling of the flameless regime has received especial attention. Weber et al. [22] modeled an industrial chamber with square cross section in steady state flameless combustion condition. Very high momentum oxidizer was charged through a central hole, NG was entered to the furnace through two injectors as a fuel and exhaust gases were recirculated in the system. In these circumstances, turbulence was modeled by standard k–ε model [23,24] and RNG k–ε model [25]. The combustion model was simulated with the eddy breakup model and a two-step reaction scheme; the eddy dissipation model (EDM) with the chemical equilibrium and the conserved scalar/prescribed probability density function (pdf) with a chemical equilibrium assumption. A similar numerical investigation was done by Kim et al. [26] who applied the standard k–ε model, the eddy-dissipation concept (EDC) and four different global reaction mechanisms. The characteristics of the MILD combustion system included a burner with a central fuel jet surrounded by six oxidizer jets and exhaust gases recirculation system was investigated numerically using k–ε and flamelet model by Coelho and Peters et al. [27] and Dally et al. [28]. It was pointed out that the numerical temperatures along the centerline of combustor were in good agreement with experimental records for pure CH_4 and CH_4 diluted with CO_2, and in poor agreement for CH_4 diluted with N_2. Khoshhal et al. [29] investigated NO_x formation and heat transfer mechanisms in a high temperature air combustion boiler numerically. It was pointed out that the experimental measured values and the CFD results illustrated good agreement. Although the temperatures of preheated oxidizer in flameless combustion mode are higher than conventional conditions, the reaction-controlling temperatures are lower than traditional combustion due to the low oxygen concentration. In the other hand, burner configuration is very important to achieve flameless conditions. In some investigations, burner contains a central inlet jet of fuel and some