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A numerical investigation of preheated diluted oxidizer influence on NO_x emission of biogas flameless combustion using Taguchi approach

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ABSTRACT

The present investigation submits an analysis about the influence of preheated diluted oxidizer parameters on NO_x emissions from a biogas flameless burner. The design parameters and their levels were diluting species, N_2 and CO_2, oxygen concentration of 5, 7 and 10% and preheated air temperature at 900, 1100 and 1300 K. An $L_{18}(2^1 3^2)$ Taguchi orthogonal array was employed to design the test plan for numerical simulations. The results reveal that an increase in oxygen concentration leads to more NO_x emissions. The same result is obtained by increasing preheated air temperature. Also, air dilution with N_2 gives better result for reducing NO_x emission compared to CO_2 dilution method. As well as, according to the ANOVA (analysis of variance), the most effective design factors on NO_x emission are oxygen concentration and then preheated air temperature with around 57% and 32% contribution, respectively, which indicates NO_x emission can be successfully enhanced by controlling these parameters.

1. Introduction

In recent years, fossil fuel resources depletion and raising rate of pollutant emission have encouraged researchers to find eco-friendly alternative fuels to the future demand [1]. Fuels derived from biomass are considered as the most promising alternative fuels to solve this problem [2]. Biogas which mainly consists of methane (CH_4) and carbon dioxide (CO_2) is known as one of the most important one in biomass category to meet a portion of energy demand of the world [1]. However, low calorific value (LCV) of biogas is one of the most important difficulties of its conversion to thermal energy [1–4]. Among various combustion techniques in order to remove this drawback, flameless combustion – also known as Moderate and Intensive Low oxygen Dilution (MILD) combustion – has gained much more attractions due to improvement in combustion efficiency and decreasing pollutant formation [2,5]. Flameless oxidation is a technique which results in a very low pollutant emissions, especially thermal NO_x and CO while improving thermal efficiency of the system [2,6]. Low oxygen concentration and dilution of air by inert gases such as CO_2 and N_2 leads the combustion mode into flameless condition [3,7].

Recently there has been a growing interest to investigate different phenomenon of biogas flameless regime either experimentally or numerically [1–4,8,9]. In all previous studies which have investigated the effect of diluted oxidizer parameters on NO_x emissions in biogas flameless regime, one-factor-at-a-time (OFAT) methodology has been employed. Moreover, no previous investigations have focused on finding the optimum system setting and the effectiveness order of diluted oxidizer parameters on NO_x pollutant emission.

In the present investigation, Taguchi approach is utilized in optimization of the factors that affect NO_x emissions of biogas flameless combustion. Taguchi optimization technique, which has recently drawn great attraction in various optimization problems, is an efficient tool to obtain optimum performance by minimizing the number of experiments [10]. Therefore, by reducing the experimental costs, Taguchi method can help us to find the most effective design parameters on the system response and also predict the performance value corresponding to optimal working conditions [10–12]. The chamber has been modeled by developing a CFD simulation code written by the authors. In the experimentation, the design parameters were diluting species, oxygen concentration and preheated air temperature, while NO_x emission was considered as a performance parameter. The conditions which leads to minimum NO_x emissions are investigated.

2. CFD modeling

In Fig. 1 the schematic of the biogas flameless chamber has been illustrated. The length and the inside diameter of the furnace are 600 mm and 150 mm, respectively. The 5 mm central inlet of the chamber is considered for biogas inlet while the other entrances are considered for the oxidizer inlets. The distance between the centerline

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Nomenclature

D_a	Damköhler number
n	the number of repetitions
S	source term
t	time (s)
u_i	velocity component (m/s)
Y_i	the response parameter value

Greek symbols

Γ	effective diffusion coefficient
Φ	diffusion parameter
ρ	density (kg/m^3)

Abbreviations

ANOVA	analysis of variance
LCV	low calorific value
MILD	Moderate and Intensive Low oxygen Dilution
CFD	Computational Fluid Dynamics
RANS	Reynolds–Averaged Navier–Stokes
DO	Discrete Ordinates
OFAT	one-factor-at-a-time
S/N	signal to noise

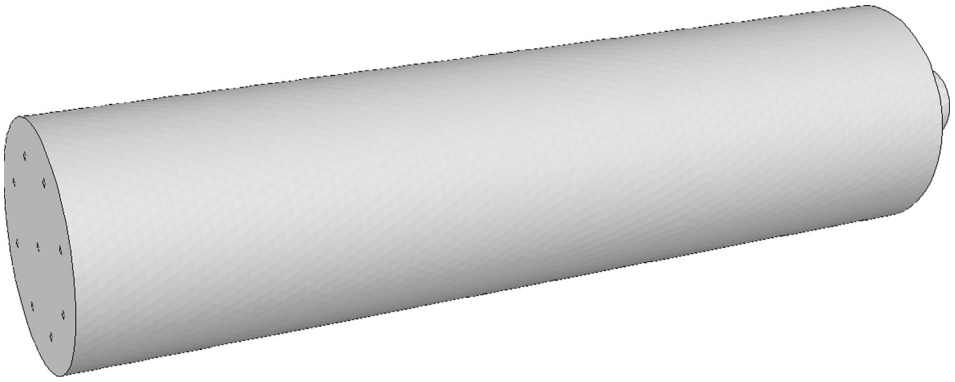

Fig. 1. Schematic of the flameless chamber.

of the fuel entrance and each oxidizer inlet is 52.5 mm. The exhaust gases are conducted to the outside of the burner through a central outlet of 50 mm diameter. It should be noticed that in order to validate the numerical model against the available experimental results, the burner dimensions and configuration are selected to be exactly the same as the flameless chamber reported by Hosseini and Wahid [1]. The simulation is done in stoichiometric ratio and the density of biogas including 60% CH_4 and 40% CO_2 in temperature of 300 K is considered 1.106 kg/m^3.

The governing equations are Reynolds–Averaged Navier–Stokes (RANS), energy and species concentration. Turbulence stresses are modeled by standard k-ε formulation due to its robustness and accuracy for a wide range of turbulent flows. Hence, two additional transport equations are needed for turbulent kinetic energy (k) and its dissipation (ε). Since Damköhler number (D_a) is greater than one due to slow mixing, eddy break-up model of Magnussen and Hjertager [13] with a two-step reaction scheme for CH_4 combustion described by Westbrook and Dryer [14] has been employed for mathematical modeling of combustion phenomenon. Therefore for each chemical species, one transport equation must be solved. NO_x formation includes two mechanisms: thermal NO_x and prompt NO_x. Zeldovich model [15] has been employed to model thermal NO_x emission in the system while prompt NO_x formation is calculated according to global model

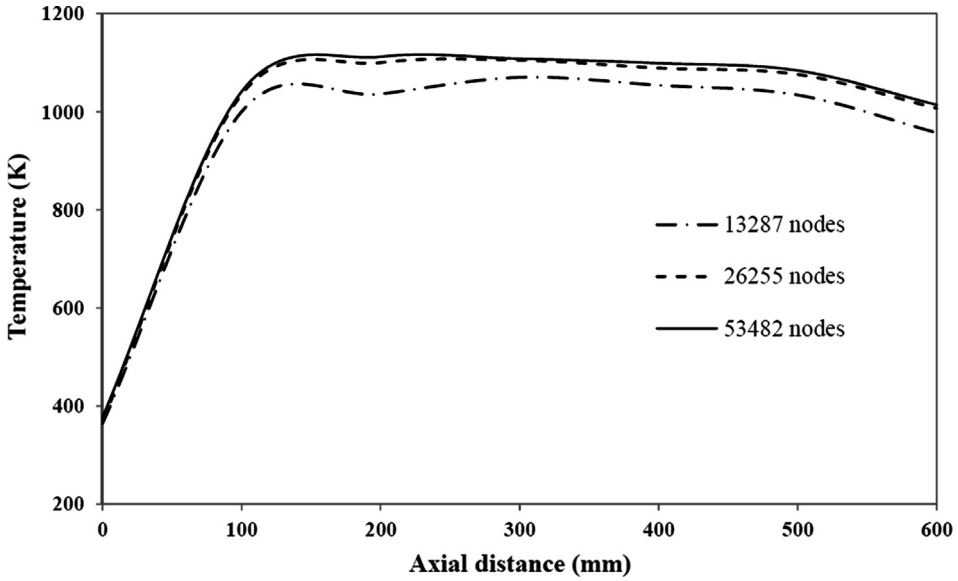

Fig. 2. Axial temperature variation for three computational grid meshes.