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Numerical study on the reburning characteristics of biomass syngas in a 2 MW pilot scale heavy oil furnace

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ABSTRACT

NOx reduction characteristics of syngas fuel were numerically investigated for the 2 MW pilot-scale heavy oil furnace of KITECH (Korea Institute of Industrial Technology). The secondary fuel, syngas, was fed into the furnace with two purposes: partial replacement of main fuel and reburning of NOx. Some portion of syngas was fed into the flame zone to replace partially the heavy oil, while the other portion was fed into the furnace downstream to reduce NOx generation. The numerical prediction was verified by comparing it to the experimental results. The syngas of KITECH's experiment, which assumedly had been produced from biomass, had a very low calorific value and contained 3% hydrocarbon. This study investigated the precise behavior of NOx generation and NOx reduction as well as the thermo-fluidic characteristics inside the furnace, which were unavailable from the experiment. In addition to 3% hydrocarbon syngas, 5% and 7% hydrocarbon syngas were numerically tested as reburning fuels to analyze the effect of hydrocarbon proportion to NOx reduction. The prediction shows that the 3% hydrocarbon syngas is equally effective as 7% hydrocarbon syngas in reducing NOx.

1. Introduction

Many shipbuilding corporations are clustered in the southern part of Korea, and they produce a large amount of wood waste. Because this type of waste has a relatively low-calorific value compared to other fossil fuels, such as coal and fuel oil, it can be used for generating steam but not for generating power. However, there is an alternative and more efficient way to use this wood waste. If this large amount of waste is transformed into syngas and is used for reburning fuel in power generation plants, it can play a key role in NOx reduction. In addition, it can partly replace main fuel in thermal equipment, such as process steam generating boilers.

Generating and using syngas is a very attractive way to secure fuel flexibility in industrial steam boilers, industrial steam generators, and electric power plants. Syngas can help to save relatively expensive fossil fuel and reduce carbon dioxide emissions. Additionally, syngas can be successfully used for NOx reduction as a reburning fuel [1]. A similar kind of energy saving and emission controlling strategy is used in the steel mill industry, where a large amount of low calorific gas is produced. The integrated steel mill industry produces a large amount of BFG (Blast Furnace Gas). This byproduct gas is used in boilers for reburning purpose, which produces process steam for steel mill industry.

A reburning technique was developed to reduce NOx emissions without after-treatment facilities by utilizing the strong capability of hydrocarbon fuel in deoxidizing NOx. Wendt et al. first reported a 50% reduction of NOx by injecting hydrocarbon fuel downstream of the primary combustion zone [2], and they called this NOx reduction technique reburning. Since then, this technique has attracted many researchers to find ways that are more efficient. Using this technique, Folsom et al. reduced NOx emissions by 60% and SO_2 by 20% [3], and they successfully reduced NOx by 55–65% in three coal-fired utility boilers [4]. Many studies continued to reveal the reburning characteristics of gas state hydrocarbon fuels such as CH_4 and C_3H_8 [5–7].

Currently, reburning fuel has a wider extent. Many researchers [8–11] proved that solid fuel, such as pulverized coal and rice bran, could be used as reburning fuel. Kicherer et al. reported that the efficiency of NOx reduction could be improved by key factors such as the high volatility of reburning fuel, long residence time, optimized mixing, and small particle diameter. Likewise, wood waste can be used as a reburning fuel in the solid state if it is crushed into fine particles. However, the use of syngas transformed from wood waste is a better solution. The feeding system of syngas is simpler

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Nomenclature

$C_{1\varepsilon}, C_{2\varepsilon}, C_\mu$	turbulence model coefficients
$C_{p,k}$	specific heat of *k*th species, J/(kg K)
h	specific enthalpy, J/kg
k	turbulent kinetic energy, m^2/s^2
$\dot m_e$	droplet evaporation rate, $kg/(m^3\ s)$
p	pressure, Pa
Pr	Prandtl number
Sc	Schmidt number
$S_{h,c}$	energy source term by combustion reaction, J/kg
$S_{ui,d}, S_{k,d}, S_{\varepsilon,d}, S_{h,d}$	source terms
T	temperature, K
u_i	velocity components, m/s
$\dot\omega_k$	reaction rate of *k*th species, $kg/(m^3\ s)$
x_i	*i* coordinate, m
Y_k	mass fraction of *k*th species

Greek symbols

ε	turbulent dissipation, m^2/s^3
μ, μ_t	molecular viscosity and turbulent viscosity, kg/(m s)
ρ	density, kg/m^3
$\sigma_k, \sigma_\varepsilon, \sigma_h, \sigma_s$	model parameters

Subscripts

i, j, k	indexes
e	evaporation

than that of fine wood particles and is easier to manage. If syngas is supplied from a large-scale syngas generation plant through a pipeline, it can be easily used for any size thermal plant from industrial steam boilers to huge electric power plants.

Syngas contains a large proportion of CO and H_2 rather than hydrocarbon components. Because only hydrocarbon radicals are major agents in the reburning process [12], syngas may be lacking in NOx reduction. In this view, Wu et al.'s result is very encouraging [1]. They proved that syngas with 7% hydrocarbon was successful in reducing NOx in a pulverized coal boiler. Yang et al. [13] made further improvements. They investigated the application in which syngas was used for the partial replacement of the main fuel as well as reburning of NOx in a pilot scale vertical oil furnace. Although they used a lower hydrocarbon percentage of syngas than Wu et al., they were successful in reducing NOx and replacing part of main fuel. They showed that even syngas with 3% hydrocarbon had a 40% NOx reduction capability.

This study numerically analyzed the combustion and reburning characteristics of Yang's experiment [13]. First, the numerical analysis was verified by comparing the measured temperature and NOx concentration with the numerical results. Because NOx concentration was measured only at the furnace exit, the experiment could investigate only the overall characteristics of NOx generation. This study investigated the precise behavior of the temperature, flow behavior, NOx generation, and NOx degeneration inside the pilot scale furnace. In addition, several computational cases were performed to study the effect of the syngas feeding rate in the flame zone and the hydrocarbon fuel percentage in the syngas composition to the overall NOx generation.

2. Mathematical formulation

2.1. Flow and energy equations

The fuel oil spray is represented by discrete droplets in the Lagrangian approach [14], while the gaseous phase flow is described in the Eulerian approach. The steady, Favre-averaged equations governing the thermo-fluidic characteristics of the gas phase can be written as [15–17]:

$$\frac{\partial \bar\rho \tilde u_j}{\partial x_j} = \tilde{\dot m}_e \tag{1}$$

$$\frac{\partial \bar\rho \tilde u_j \tilde u_i}{\partial x_j} = -\frac{\partial \tilde p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\left(\frac{\partial \tilde u_i}{\partial x_j}+\frac{\partial \tilde u_j}{\partial x_i}\right) - \left(\frac{2}{3}\mu\frac{\partial \tilde u_k}{\partial x_k}\right)\right] + \tilde S_{ui,d} \tag{2}$$

$$\frac{\partial(\bar\rho k)}{\partial t} + \frac{\partial \bar\rho \tilde u_j k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] - \overline{\rho u_i'' u_j''}\frac{\partial \tilde u_j}{\partial x_i} - \bar\rho\varepsilon + \tilde S_{k,d} \tag{3}$$

$$\frac{\partial(\bar\rho \varepsilon)}{\partial t} + \frac{\partial \bar\rho \tilde u_j \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - C_{1\varepsilon}\frac{\varepsilon}{k}\left(\overline{\rho u_i'' u_j''}\frac{\partial \tilde u_j}{\partial x_i}\right) - C_{2\varepsilon}\bar\rho\frac{\varepsilon^2}{k} + \tilde S_{\varepsilon,d} \tag{4}$$

$$\frac{\partial \bar\rho \tilde u_j \tilde h}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{Pr}+\frac{\mu_t}{\sigma_h}\right)\frac{\partial \tilde h}{\partial x_j}\right] + \tilde S_{h,c} + \tilde S_{h,d} \tag{5}$$

$$\frac{\partial \bar\rho \tilde u_j \tilde Y_k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu}{Sc}+\frac{\mu_t}{\sigma_s}\right)\frac{\partial \tilde Y_k}{\partial x_j}\right] + \tilde{\dot m}_{e,k} + \tilde{\dot\omega}_k \tag{6}$$

where

$$\mu_t = \bar\rho C_\mu \frac{k^2}{\varepsilon} \tag{7}$$

$$\overline{\rho u_i'' u_j''} = \mu_t\left(\frac{\partial \tilde u_i}{\partial x_j}+\frac{\partial \tilde u_j}{\partial x_i}\right) - \frac{2}{3}\left(\mu_t\frac{\partial \tilde u_k}{\partial x_k} + \bar\rho k\right)\delta_{ij} \tag{8}$$

$$\tilde h = \sum_k \tilde Y_k \int_{T_{ref}}^{T} C_{p,k}\, dT \tag{9}$$

The interaction between the fuel oil droplets and gas flow is expressed as the source terms in Eqs. (1)–(6). $\tilde{\dot m}_e$ is the added mass by droplet evaporation. $\tilde S_{ui}$ consists of the drag force exerted by the droplets and the momentum of the evaporated fuel. $\tilde S_{k,d}$ and $\tilde S_{\varepsilon,d}$ are the turbulent kinetic energy source and dissipation rate source aroused by the evaporating droplets, respectively. The energy source term, $\tilde S_{h,d}$, is the net energy transfer from the gaseous phase to the droplets. $\tilde S_{h,c}$ and $\tilde{\dot\omega}_k$ represent the energy source term and the generation rate of *k*th species by the combustion reaction, respectively.

The Eddy dissipation model, designed by Magnussen and Hjertager [18], is used to calculate $\tilde{\dot\omega}_k$ in Eq. (6). Although this turbulent combustion model is simple, it is well behaved for the ordinary turbulent diffusion flame developed by the combustion of oil and pulverized coal in boiler furnaces, unless there is no extinction of flame. The gas phase mixture and droplets are involved in the radiation heat transfer. The radiant intensity Eq. [19] is solved with DOM (discrete ordinate method) [20]. The radiation is coupled with the energy equation as the form of radiation flux divergence, which represents the net absorbed radiation by the gas medium.