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Research paper

Development of an oxygen-enhanced combustor for scrap preheating in an electric arc furnace

Jeongseog Oh*, Eungyeong Lee, Dongsoon Noh

Advanced Combustion Laboratory, Korea Institute of Energy Research, Daejeon, Republic of Korea

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ABSTRACT

The performance of a pilot-scale oxygen-enhanced furnace for scrap preheating with a multi-nozzle inverse diffusion combustor was studied. Natural gas and oxygen diluted in air were supplied to the oxygen-enhanced combustor with a range of 120–300 Mcal/h. The internal flow field of the furnace was simulated with a computational fluid dynamics program before any experiments were carried out. Meanwhile, the characteristic time for furnace heat-up and the level of pollutant emission were experimentally measured. Results showed that the temperature rise in the furnace increased steeply with an increase in the oxygen mole fraction in an oxidant. In addition, the characteristic time for furnace heat-up decreased exponentially as the thermal input power increased.

1. Introduction

Air-used combustion is a method that is commonly used in the steel melting or reheating processes. In recent, oxygen-enhanced or oxygen-enriched combustion (OEC) is introduced to increase thermal efficiency [1]. Steel and iron have served as basic materials for industry. The steel making process is classified as either blast furnace or electric arc furnace (EAF) method. Compared to the blast furnace, on advantage of the EAF method is increased energy savings due to the simple process and the low emission of carbon dioxide (CO_2) [2]. In particular, this is relevant today because of the world wide attempts to reduce CO_2 emissions due to global warming and climate change [3].

A new method for an effective thermochemical steel-making using in EAF process is needed to reduce energy consumption. Several alternatives that have been suggested use heat recovery from burned gas (i.e. flue gas), such as the Eco-Arc and Consteel processes [4,5]. The core concept of both methods is scrap preheating up to 600 °C with high temperature flue gas (about 1200 °C). As a secondary thermal energy source into relatively cold zone, OEC and carbon lancing play an important role in increasing electric energy savings. This thermochemical method is one of ways to reduce electricity usage by removing the energy conversion process of fossil fuel energy to electric energy.

OEC is characterized by a higher flame temperature than that of air-used combustion because a higher oxygen concentration in an oxidant leads to a lower absorption energy by nitrogen (N_2). This characteristic of the high temperature has been used in heat treatment furnaces, waste incinerators, propulsion engines, etc. Compared to air-used combustion, OEC is known to increase reaction rate due to the higher flame temperature and oxygen mole fraction in the same flow condition. Wu et al. [6] reported that a small amount of oxygen added to an oxidant (e.g. 21%–30%) resulted in a fuel consumption decrease of 26.1%.

Increased OEC is good for not only energy savings, but also for productivity improvement. Bělohradský et al. [7] reported that combustion efficiency is influenced by the mole fraction of O_2 in an oxidant (X_{O_2}) due to an increased CO_2 and water vapor (H_2O) mole fraction in flue gas. A flue gas temperature is in inverse proportion to the time needed for the heat transfer to the object being heated, such as iron nuggets and ingots.

However, a weakness of OEC is the additional costs related to the increased oxygen supply and burner retrofitting because the increased combustion intensity leads to a high temperature environment in the furnace and the exposure of the burner surface to this heat level results in a need for more frequent maintenance. A method using CO_2 recirculation has been suggested to control reaction rate and flame temperature [8]. CO_2 dilution to an oxidant is effective in reducing the production of thermal nitrogen oxides (NO_x).

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* Corresponding author. Advanced Combustion Laboratory, Korea Institute of Energy Research, Daejeon 305-343, Republic of Korea. Tel.: +82 42 860 3479; fax: +82 42 860 3133.
E-mail address: jeongs5@kier.re.kr (J. Oh).

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Nomenclature

a.u.	arbitrary unit
CCS	carbon capture and storage
c_{pi}	specific heat of species *i* (cal/(g × K))
DO	discrete ordinate model
d_A	outlet diameter in an air nozzle exit (mm)
d_F	outlet diameter in a fuel jet nozzle exit (mm)
d_{Ox}	outlet diameter in an oxygen nozzle exit (mm)
EAF	electric arc furnace
EDM	eddy-dissipation model
EDC	eddy-dissipation concept model
EI_i	emission index of species *i* (g/kg)
LHV_i	low heating value of species *i* (kcal/Nm^3)
lpm	liter per minute
MFC	mass flow controller
MWi	molecular weight of species *i* (g/kg)
m_i	mass of species *i* (g)
NG	natural gas
NTP	normal temperature and pressure (300 K and 1 bar)
OEC	oxygen-enhanced combustion
Q_{Th}	thermal input power of fuel (Mcal/h or kW)
P_∞	atmospheric pressure (bar)
ΔP	pressure difference between the inside of furnace and the atmosphere (mm H_2O)
RANS	Reynolds averaged Navier–Stokes
RKE	realizable $k-\varepsilon$ model
r	transverse distance (mm)
SIMPLE	semi-implicit method for pressure linked equations
SKE	standard $k-\varepsilon$ model
TC#n	n-th thermocouple (ea.)
T_{Ad}	adiabatic flame temperature of an oxygen-enhanced flame (K or °C)
T_i	temperature of species *i* (°C or K)
T_m	volume-averaged temperature in a furnace (°C or K)
T_∞	surrounding temperature (°C or K)
u_A	velocity in an air nozzle exit (m/s)
u_F	velocity in a fuel jet nozzle exit (m/s)
u_{Ox}	velocity in an oxygen nozzle exit (m/s)
u^*	friction velocity
V_i	volumetric flow rate of species *i* (lpm or Nm^3/h)
X_i	volumetric mole fraction of species *i* (%)
$X_{i,st}$	volumetric mole fraction of species *i* under stoichiometric conditions (%)
x	streamwise distance (mm)
y^+	y-plus
y^*	y-star ($=(\mu_i/\rho_i) \times (y^+/u^*)$)
z	vertical distance (mm)
ε_c	combustion efficiency (%)
μ_i	viscosity of species *i* (kg/(m × s))
ϕ_G	global equivalence ratio
ρ_i	density of species *i* (kg/m^3)

The variation of the combustor wall divergence is known to influence the flow stream and recirculation zone in the combustor. Tu et al. [9] investigated the geometry effect of the wall divergence on the performance of a swirl stabilized burner. They reported that OEC is one of useful methods for designing a compact combustor. Previous studies in the field of OEC are summarized in Table 1 [6–10].

In the current study, the performance of an oxygen-enhanced combustor was numerically simulated and experimentally investigated to develop a pilot-scale scrap preheating furnace. An inverse diffusion type of multi-nozzle burner was used for a non-premixed oxygen-enhanced natural gas flame. The objective of the present work was to study the thermal characteristics of the pilot-scale oxygen-enhanced combustor and to optimize the effectiveness of using working fluid for scrap preheating.

2. Experimental methods

A pilot-scale oxygen-enhanced combustor was developed to simulate the scrap preheating process in an EAF. Fig. 1(a) shows the geometry and dimension of a pilot-scale EAF simulator. The flow direction of the burned gas is marked by a red (in the web version) arrow along the exhaust pipe. The width (*W*), height (*H*), and depth (*D*) of the oxygen-enhanced furnace was 3.0, 1.0, and 1.0 m, respectively. The inside wall of the furnace was insulated with ceramic fiber board (FXL D-Block, ITM Co., Ltd., Kozaki, Chiba Prefecture, Japan) to minimize heat loss. The positive pressure difference between furnace inside and surrounding air (ΔP) was kept constant at about 5 ± 1.5 mm H_2O to prevent air intrusion into the furnace. An oxygen-enhanced combustor was installed in the left-side wall of the furnace.

The pilot-scale burner used in the current study was designed as an inverse-diffusion type with multiple nozzles. An oxygen nozzle was located in the center of the burner, while 8 fuel jet nozzles were located around the oxygen nozzle. Eight air nozzles were located around the fuel nozzle to reduce the fluctuation of the oxygen-enhanced flame base. The diameters of fuel jet, oxygen, and air nozzle exits were $d_F = 11.5$ mm, $d_{Ox} = 18.2$ mm, and $d_A = 25.0$ mm, as shown in Fig. 1(b).

Gas-phase oxygen (99.0% purity; Daesung industrial gases Co., Daejeon, Korea) was supplied through a delivery pipe and an air-cooled evaporator connected to a liquefied oxygen tank. The composition of natural gas (NG) was 91.6% methane (CH_4), 5.8% ethane (C_2H_6), 1.7% propane (C_3H_8), 0.8% butane (C_4H_{10}), and 0.1% nitrogen (N_2) (Chungnam City Gas Co., Daejeon, Korea). The composition of the surrounding air was assumed to be 21% oxygen (O_2) and 79% N_2 by volume.

The mass flow rate of the NG, O_2, and air was regulated with orifices (SOP–SOF; Samil Industry Co., Incheon, Korea), a control valve (VM-1100; Seojeon VALMAC Co., Daejeon, Korea), and mass flow controllers (5851E; Brooks Instrument Co., Hatfield, PA, USA). The mass flow controller (MFC) was calibrated using a dry gas meter (DA-16A-T; Sinagawa Co., Tokyo, Japan) before installation. The linearity of a flow rate control system was over 99.0% in 50–500 lpm in a manual.

The volume-averaged temperature was measured with R-type thermocouples (TCs). These TCs were equipped on a side wall of the furnace, as shown in Fig. 1(a). The location of the TC junction (i.e. temperature measuring point) extruded 100 mm toward the inside of the furnace from the wall surface. The diameter of thermocouple junction at a thermocouple tip was about 500 μm. The radiation heat loss at the junction point, the conductive heat loss along the thermocouple wires, and the catalytic reaction on the surface of the thermocouple wires were neglected in the current study. The tolerance of TCs was estimated about 0.25% in the range of 0–1450 °C in a specification sheet.

A gas analyzer for nitrogen monoxide (NO) (Ultramat 6; Siemens Co., Munich, Germany), carbon monoxide (CO) (AO2020; ABB Co., Zurich, Swiss), and CO_2 (Ultramat 32; Siemens Co., Munich, Germany) was used to measure the level of pollutant emissions in the