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Research paper

Improvement in thermal efficiency of regenerator system by using oxy-fuel combustion

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HIGHLIGHTS

- General regenerator systems are not compatible with oxy-fuel combustion because of low thermal efficiency.
- New operating methods are considered for regenerator system by using oxy-fuel combustion.
- Temperature of gas passing through regenerator is measured for different operating methods and design parameters.
- Temperature characteristics are significantly affected by different operating methods.
- Both exhaust gas bypass and CO_2 recirculation methods improve thermal efficiency.

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ABSTRACT

In this experimental study, a new system combining the oxy-fuel combustion with the concept of regeneration is developed. The performance of the regenerator system, which consists of a pair of oxy-fuel burners and regenerators, is demonstrated. To improve the thermal efficiency of the oxy-fuel combustion-based regenerator system, new methods are considered, such as exhaust gas bypass and CO_2 recirculation. The regeneration characteristics obtained when using oxy-fuel combustion are investigated by applying each method to the oxy-fuel combustion-based regenerator system.

The temperature variation in the gas passing through the regenerator is significantly affected by the different operating methods and design parameters such as the switching time, regenerator configuration, and regenerator weight. The reference method, which is the same as air-fuel combustion, shows a low heat recovery ratio in the regenerator, whereas the exhaust gas bypass method has the highest value of the heat recovery ratio, followed by the CO_2 recirculation method, because of an improvement in the enthalpy imbalance between the exhaust gas and regeneration gas. From the study results, it is confirmed that the use of the exhaust gas bypass method or CO_2 recirculation method should be effective in improving the thermal efficiency of the oxy-fuel combustion-based regenerator system.

1. Introduction

Combustion-based regenerator systems have found broad industrial applications because they have high thermal efficiency owing to the fact they re-use waste heat. Many studies have been conducted to investigate the characteristics and optimization of regenerator systems. Monte [1] conducted an analytical study on the counter-current regeneration in steady flows. Noh et al. [2] performed an experimental study on regenerator and proposed a correlation of the thermal efficiency for designing a regenerator. Zarrinehkafsh et al. [3] suggested both mathematical and experimental approaches for the analysis of a regenerator packed with alumina balls. Rafidi et al. [4] developed a two-dimensional simulation model of a honeycomb regenerator and estimated the dynamic temperature and velocity profiles of the working gases in the regenerator. Jia et al. [5] simulated the heat transfer in a honeycomb regenerator with respect to several parameters such as the switching time and inlet gas temperature. Ai et al. [6] studied the heat transfer characteristics in the regeneration process and proposed an analytical solution on temperature profile of flue gas and regenerator.

Owing to the increasing complexity of the problem of global warming, carbon capture and storage (CCS) technologies have attracted considerable interest. The many CCS technologies that

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Nomenclature

H	heat recovery ratio (dimensionless unit)
T	temperature (°C)
$\overline{T}$	time-averaged temperature (°C)
t	time (s)
C_P	specific heat (kJ/kg-K)
M	mass flow rate (kg/s)
τ	time constant (s)

Subscripts

1,2	measurement position
atm	atmosphere temperature (20 °C)
h	exhaust gas at heating process
r	regeneration gas at regeneration process
c	compensated data
m	measured data

have been developed include oxy-fuel combustion, wherein fuel is burned using pure oxygen instead of air [7–11].

Concerns about energy conservation and the environment have led to recent interest in the study and development of a new regenerator system based on oxy-fuel combustion. For example, Hong et al. [12] performed experiments on a lab-scale regenerator system that used oxy-fuel combustion. Kang et al. [13] compared the numerical and experimental results obtained for a regenerator system that used oxy-fuel combustion. The finding of these studies indicated that the use of oxy-fuel combustion in general regenerator systems reduced the thermal efficiency. The low efficiency has been attributed to the occurrence of enthalpy imbalance between the exhaust gas and the oxygen in the regenerator, unlike when air-fuel combustion is employed [12,13].

Owing to the need to improve the thermal efficiency of regenerator system with oxy-fuel combustion, new regenerator systems that utilize exhaust gas bypass and CO_2 recirculation are proposed in this paper. The temperature and thermal efficiency characteristics of the proposed systems are experimentally investigated using different operating methods and design parameters such as the switching time, regenerator configuration, and regenerator weight.

2. Experimental apparatus

2.1. Experimental apparatus

Fig. 1 shows the experimental apparatus, which consists of a pair of burners and regenerators, a combustion chamber, a main induced draft fan, an exhaust gas bypass sub-system, and a CO_2 supply system. By controlling the switching valve, one burner is switched on when the other burner is kept off and vice versa; the on and off durations are determined by the parameter called the switching time. The two regenerators have different shapes as shown in Fig. 1. Ceramic honeycombs and balls made from 100% cordierite were used as the regenerator materials. The honeycombs had a diameter of 70 mm. Honeycombs having cell densities and lengths of 300 cells/in^2 and 200 mm and 300 cells/in^2 and 100 mm, respectively, were considered. The balls had a diameter of 5 mm and were contained in a bespoke cartridge, with the total weight being 404 and 606 g. A ceramic insulator was installed around the regenerators to minimize heat loss. LNG gas was supplied to the burner at 13.6 L per minutes, which is equal to 10 kW based on the higher heating value of the gas, and the oxygen/fuel ratio was fixed to 1.2. In the experimental condition, the temperature in the combustion chamber was maintained at 1500–1600 °C. The temperature of the working fluid passing through the regenerator was measured using K-type thermocouples at the center of the regenerator cross section (at positions 1 and 2), as shown in Fig. 2. In this study, switching times of 60, 120, and 180 s were considered based on the range of typical switching times of general regenerator systems.

Fig. 2 shows schematics of the different operating methods of the proposed regenerator systems. Fig. 2(a) shows the reference case, which is the same as the general regenerator system based on air-fuel combustion. This case involves two processes: heating process and regeneration process (Fig 2(a)). In the heating process, the hot gas exhausted from the combustion chamber passes through the regenerator. The heat of the exhaust gas is stored in the

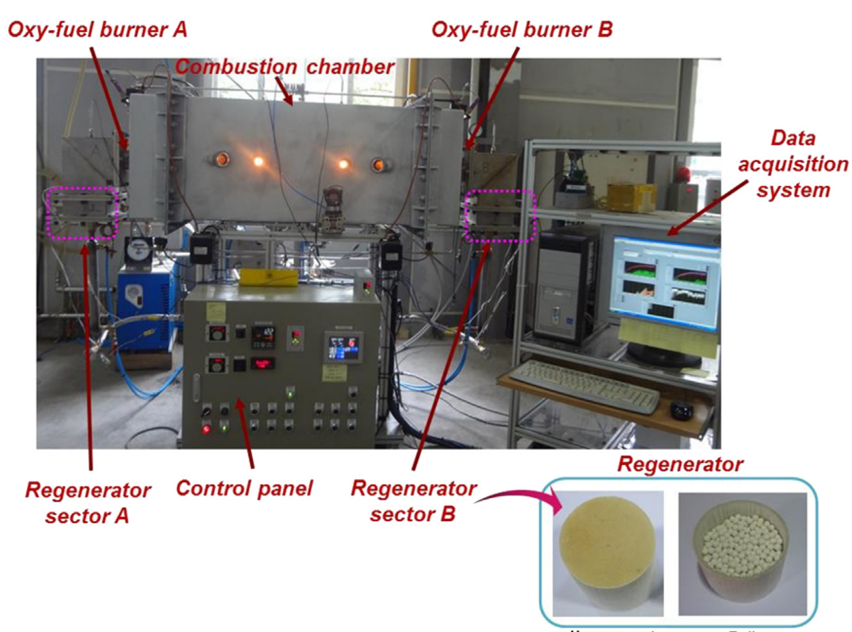

Fig. 1. Experimental apparatus.