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Heat transfer characteristics of a ceramic honeycomb regenerator for an oxy-fuel combustion furnace

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HIGHLIGHTS

- The regenerative system of an air–fuel system is not applicable to an oxy-fuel one.
- The temperature and pressure of a honeycomb regenerator are measured.
- Bypassing of 40% of exhaust gas is needed to avoid the saturation of regenerator.
- A longer honeycomb and shorter switching time show better temperature efficiency.
- We incorporate effect of the length, diameter and switching time into one curve.

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ABSTRACT

Regenerative furnaces have been widely used to reduce waste heat, and to achieve constant temperature distribution in a furnace. However, direct application of the regenerative system for an air–fuel combustion furnace to an oxy-fuel combustion furnace is not possible, because of much higher volume flow rate in air–fuel combustion than the volume flow rate in oxy-fuel combustion. We therefore experimentally and numerically study the heat transfer performance of a ceramic honeycomb regenerator in oxy-fuel combustion. The pressures and temperatures in a regenerator are measured, and compared with numerical simulation that is calculated by using the CFD code, FLUENT, resulting in agreement. Numerical simulation shows that bypassing of ~40% of the exhaust gas is essential, to prevent saturation of the honeycomb regenerator. Analysis of experimental data presents that a longer honeycomb and shorter switching time show better efficiency.

1. Introduction

Pure oxygen–fuel combustion technology is a popular carbon capture technology that burns fossil fuel with high purity oxygen instead of air, and is able to achieve a high combustion rate, less fuel consumption, smaller exhaust gas, and ideally zero NOx emission, due to the shut-off of the supply of nitrogen [1–3]. However, oxy-fuel combustion has not been widely commercialized, because of the higher cost than that of air–fuel combustion, too high flame temperature, worse temperature distribution in the furnace, and possible air leakage that can produces a large amount of NOx [2]. To reduce the cost of oxy-fuel combustion, and to ultimately reduce the carbon dioxide emission, the efficiency of oxy-fuel combustion should be increased.

Regenerative furnaces have been widely used in the steel-making industry to reduce the heat losses of exhaust gas that account for the greatest percentage of thermal loss [4–11]. Many regenerative furnaces are equipped with alternate switching type regenerative burners that use regenerative porous media, such as ceramics spheres, or honeycomb. The alternate switching type regenerative combustion system consists of two burners as shown in Fig. 1(a). One burner produces flame with preheated air, while the other burner passes the exhaust gas to the regenerative porous media, to recycle waste heat. After switching the cycle, the burner that had passed the exhaust gas in a previous cycle, produces the flame with air preheated by reserved heat in the regenerative porous media. Simultaneously, the burner that had produced flames in a previous cycle passes exhaust gas to the regenerative porous media. Fuel saving can reach up to 45%, and productivity

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Nomenclature

A	area
d	hydraulic diameter of a cell
E	energy
K	permeability
k	conductivity
L	length of honeycomb
n	number of cells
Q	volume flow rate
p	pressure
t	time
T	temperature
u	velocity
x	coordinate direction

Greek symbols

ε	porosity
Φ	viscous dissipation
η	efficiency
μ	viscosity
ρ	density
τ	time constant

Subscripts

1,2	Point 1 and 2, respectively
c	compensated data
cell	per cell
eff	effective
f	fluid
g	exhaust gas
h	heating process
m	measured data
o	oxygen
pass	per switching time
r	regenerating process
s	solid

improvement up to 20%. Constant temperature distribution in a furnace can also be achieved by stimulated flow through the repeated switching cycle.

To the authors' knowledge, regenerative combustion technology has never been applied to an oxy-fuel combustion furnace. Since the volume of oxygen in oxy-fuel combustion is much less than the volume of air in air–fuel combustion, the required heat for preheating the oxygen in oxy-fuel combustion is also smaller than the required heat for preheating the air in air–fuel combustion. The reaction formula in air–fuel combustion with methane as a fuel is as follows:

$$CH_4 + 2O_2 + 8N_2 \rightarrow CO_2 + 2H_2O + 8N_2 \quad (1)$$

If 1 mol of methane is used in air–fuel combustion, 11 mol of exhaust gas consisted of CO_2, H_2O and N_2 should preheat 10 mol of air. Since the volume of exhaust gas almost matches the volume of air, saturation of the porous regenerator is not matter in air combustion. Usually the fuel is not preheated, for the safety of system. In the case of oxy-fuel combustion, N_2 is absent. This represents that the 3 mol of exhaust gas should heat 2 mol of oxygen, implying an imbalance between the offered heat from the exhaust gas and the required heat in the oxygen. In terms of enthalpy, the enthalpy of heated oxygen is ~60% of enthalpy of exhaust gas. This imbalance might saturate the regenerative porous media, or decrease energy efficiency. Moreover, the temperature of the exhaust gas from oxy-fuel combustion is higher than the temperature from air–fuel

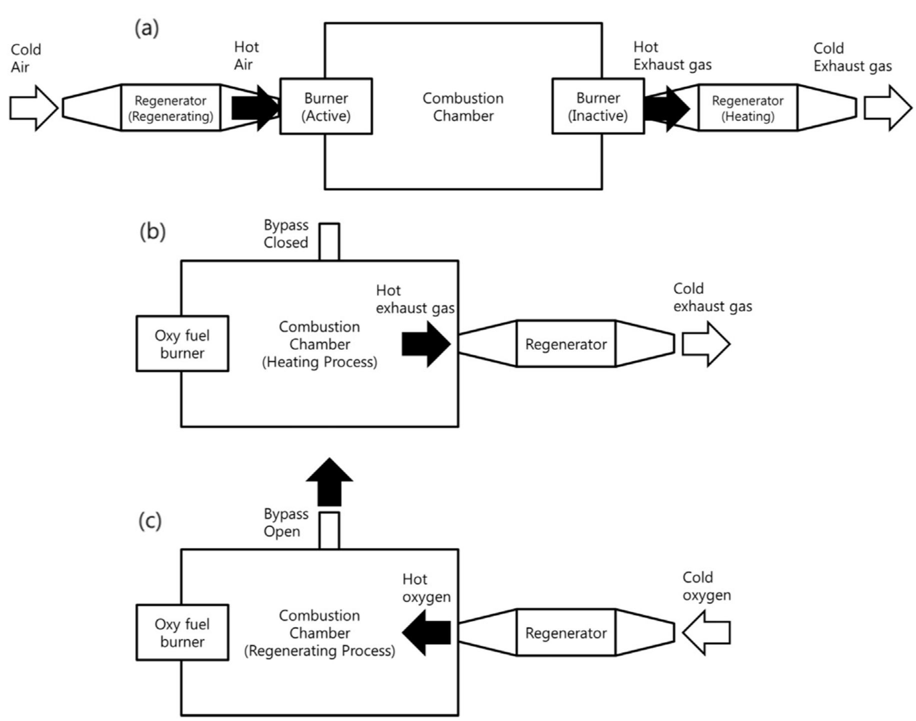

Fig. 1. Schematic diagrams of real regenerative combustion system and the experimental setup. (a) Real regenerative system, (b) experimental setup in heating process, and (c) experimental setup in regenerating process.