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Study on the combustion characteristics of a premixed combustion system with exhaust gas recirculation

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ABSTRACT

The boiler of a premixed combustion system with EGR (exhaust gas recirculation) is investigated to explore the potential for increasing thermal efficiency and lowering pollutant emissions. To achieve this purpose, a thermodynamic analysis is performed to predict the effect of EGR on the thermodynamic efficiency for various equivalence ratios. Experiments of a preheated air condensing boiler with EGR were conducted to measure the changes in the thermal efficiency and the characteristics of the pollutant emission. Finally, a 1-D premixed code was calculated to understand the effect of the EGR method on the NO reduction mechanism. The results of the thermodynamic analysis show that the thermodynamic efficiency is not changed because the temperature and the amount of the exhaust gas are unchanged, even though the EGR method is implemented in the system. However, when the EGR method is used with an equivalence ratio near 1.00, it is experimentally verified that the thermal efficiency increases and the NO_x concentration decreases. Based on the results from numerical calculations, it is shown that the NO production rates of $N + O_2 \leftrightarrow NO + O$ and $N + OH \leftrightarrow NO + H$ are remarkably changed due to the decrease in the flame temperature and the NO mole fraction is decreased.

1. Introduction

As industrial development has rapidly increased in recent years, the problems of excessive energy consumption and environmental pollution due to increasing generation of exhaust gas have become a social issue. Various types of combustion systems have already been studied and developed to solve these problems, and research in renewable energy fields such as hydrogen, solar and bio energy is being conducted. However, the results are not as satisfactory as was expected. Thus, the most realistic and economical method to solve the problems of excessive energy consumption and environmental pollution is to conduct research in combustion systems that use fossil fuels with the goal of achieving high thermal efficiencies and low pollutant emissions.

Combustion with EGR (exhaust gas recirculation) is one among recent, representative low-pollutant combustion methods and has widely been applied. EGR has the advantage of being applicable to any type of combustion system because it reuses the exhaust gas produced from the combustion process. However, most research regarding EGR is limited to automotive internal combustion engines, and no research has been conducted on small-scale household combustion systems with premixed flames. Rather, most research presently focuses on large-scale industrial combustion systems with non-premixed flames. For research on internal combustion engines with the EGR method, Park et al. [1] showed that EGR with optimized ignition timing for a spray-guided combustion system in a gasoline direct injection engine can reduce harmful NO_x and THC emissions effectively. Yadav et al. [2] reported that dual fuel operation with hydrogen induction coupled with exhaust gas recirculation results in lowered emission levels and improved performance levels for a direct injection diesel engine, Lakshmanan and Nagarajan [3] showed reduced NO_x emissions and improved part load performances for an acetylene induction diesel engine with cooled EGR. In research on non-premixed flames applied EGR method, Shinomori et al. reported that NO_x emission for small boiler can be reduced approximately 80% when the amount of a recirculating gas was increased to 50% [4]. Kim et al. investigated the NO emission characteristics for the oxy-fuel combustors using FGR (flue gas recirculation) technology experimentally [5]. In this study, they showed that the reduction ratio of NO emission was more than approximately 85% when the combustor was operated at the 40% FGR ratio and they also verified that the FGR technology was quite effective for reducing the NO emission in the oxy-fuel combustor. Baltasar et al. presented an

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experimental and numerical study of the effect of FGR (flue gas recirculation) on flame characteristics and pollutant emissions for a small-scale laboratory furnace [6]. In this study, they showed that the flue gas decreased NO_x emissions with FGR without significant effects on flame stability, overall combustion efficiency and CO emission. In addition, Jiang et al. reported the result of NO_x reduction for an industrial reheating furnace with flue gas recirculation [7].

A typical, present-day combustion system that has been adapted to use premixed flames is described by an equivalence ratio, which is the ratio of the stoichiometric air–fuel ratio to the actual air-fuel ratio. Most premixed combustion systems are operated near an equivalence ratio of 0.70 to reduce pollutant emissions such as nitrogen oxides (NO_x) and to ensure complete combustion of the fuel. However, combustion systems at this operating condition have a limited maximum theoretical thermal efficiency [8]. Table 1 shows the characteristics of combustion systems by equivalence ratio. Specifically, the thermal efficiency of a combustion system is represented by the ratio of the useful output of a device to the input in terms of energy. Thus, as shown in Table 1, if the system were operating below an equivalence ratio of 1.00 with the same input heat, the thermal efficiency decreases with decreasing flame temperature and the amount of exhaust gas, i.e., the displacement volume, increases. However, if the system were operating near an equivalence ratio of 1.00, from an energy-saving point of view, the thermal efficiency of the system increases with increasing flame temperature and the amount of exhaust gas decreases. Of course, increasing the flame temperature can cause durability problem, and has a disadvantage in that it increases NO_x emissions. Generally, in combustion systems, the trade-offs between the thermal efficiency and the pollutant emissions are described by the equivalence ratio. Thus, if the combustion system is operating near an equivalence ratio of 1.00, an increase in the thermal efficiency must be coupled with the introduction of low-pollutant emission combustion methods to decrease pollutant emissions.

In previous works [9,10], Yu et al. suggested the possibility of using the EGR method for a premixed combustion system, especially a small-scale household boiler and the optimal burner material for the EGR boiler. Specifically, we have studied the effect of EGR on the thermal efficiency and pollutant emission characteristics for various EGR ratios and equivalence ratios, and it was shown that the EGR method is advantageous from the standpoint of reducing emission concentrations and ensuring the combustion stability of the burner. However, although we have confirmed the possibility of using the EGR method for a small-scale, premixed combustion system, these results do not accurately represent a real combustion system because the main burner and EGR burner were used separately to produce the exhaust gas. Thus, in this study, EGR method is applied to a real, household premixed combustion system to improve and supplement the problem in the previous work.

In view of the above considerations and the extension of the previous work, the purpose of this study is the fundamental understanding of the effect of EGR on the premixed combustion system. To achieve this purpose, the thermodynamic analysis is first performed to predict the effect of EGR on the thermodynamic efficiency for the preheated air condensing boiler with various equivalence ratios. Second, the EGR method that is applied to a preheated air condensing boiler, which is a representative household premixed combustion system, is experimentally tested to measure the change in the thermal efficiency and the characteristics of the pollutant emission for the system with various equivalence ratios and EGR ratios. Here, it notes that since the thermodynamic efficiency and the thermal efficiency are the same thing, differing only because the first one is calculated on a thermodynamic basis while the second one estimated experimentally. Finally, a 1-D premix code with a detailed chemical reaction mechanism is constructed to numerically understand the fundamentals of the effect of EGR on the characteristics of pollutant emissions.

Table 1
Characteristics of a combustion system by equivalence ratio.

Item	$\Phi \approx 1.00$	$\Phi << 1.00$
Amount of exhaust gas	Decrease	Increase
Flame temperature	Increase	Decrease
Thermal efficiency	Advantage	Disadvantage
Low pollutant	Disadvantage	Advantage
Durability of system	Disadvantage	Advantage

2. Research methods

2.1. Thermodynamic analysis

As mentioned above, a thermodynamic analysis is performed to predict the effect of EGR on the thermodynamic efficiency for the preheated air condensing boiler with various equivalence ratios. For the thermodynamic analysis calculations, the fuel is assumed to be methane for the convenience of the analysis, and the pressure of the exhaust gas and the ambient temperature are assumed to be 1 atm and 273 K.

The stoichiometric reaction of methane, the inlet and the outlet heat of the system and the thermodynamic efficiency used in the thermodynamic analysis are shown in Eqs. (1)–(4). Here, the calculation of the thermodynamic efficiency is considered by including the heat recuperated through condensation of water vapor based on the exhaust gas temperature [11,12].

$$N_{CH_4}CH_4 + \frac{2}{\Phi}(O_2 + 3.76N_2) \Rightarrow N_{CO_2}CO_2 + N_{H_2O}H_2O + N_{O_2}O_2 + N_{N_2}N_2, \tag{1}$$

$$Q_{in} = H_{PROD}\left(T_{ref}\right) - H_{REAC}\left(T_{ref}\right), \tag{2}$$

$$Q_{out} = H_{PROD}\left(T_{ref}\right) - H_{PROD}(T_{out}), \tag{3}$$

$$\eta_{TD} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{H_{PROD}\left(T_{ref}\right) - H_{PROD}(T_{out})}{H_{PROD}\left(T_{ref}\right) - H_{REAC}\left(T_{ref}\right)}. \tag{4}$$

In Eqs. (1)–(4), N is the number of moles of the species (a subscript indicates the species name), Q is the inlet (with a subscript in) and outlet (with a subscript out) heat, H is the enthalpy of the product (with a subscript PROD) and reactant (with a subscript REAC), T is the product (with a subscript PROD) and ambient (with a subscript ref) temperature, and η_{TD} is the thermodynamic efficiency by the thermodynamic analysis. For the calculation, the equivalence ratio is varied between 0.60, 0.80 and 1.00, and the temperature of exhaust gas is changed from 275 K to 420 K.

2.2. Experimental method

Fig. 1 shows the schematic illustration of the condensing boiler used in this study. As Fig. 1 shows, the premixed porous-media burner is installed at the top of the boiler; the burner is a metal fiber burner with a porosity of approximately 89%. The total burner size is 187 mm × 73 mm, and the size of combustion surface is