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An analysis of the thermodynamic efficiency for exhaust gas recirculation-condensed water recirculation-waste heat recovery condensing boilers (EGR-CWR-WHR CB)

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ABSTRACT

This study presents fundamental research on the development of a new boiler that is expected to have a higher efficiency and lower emissions than existing boilers. The thermodynamic efficiency of exhaust gas recirculation-condensed water recirculation-waste heat recovery condensing boilers (EGR-CWR-WHR CB) was calculated using thermodynamic analysis and was compared with other boilers. The results show the possibility of obtaining a high efficiency when the temperature of the exhaust gas is controlled within 50–60 °C because water in the exhaust gas is condensed within this temperature range. In addition, the enthalpy emitted by the exhaust gas for the new boiler is smaller because the amount of condensed water is increased by the high dew-point temperature and the low exhaust gas temperature. Thus, the new boiler can obtain a higher efficiency than can older boilers. The efficiency of the EGR-CWR-WHR CB proposed in this study is 93.91%, which is 7.04% higher than that of existing CB that is currently used frequently.

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1. Introduction

As industrial development has continued in recent years, the use of combustion systems that use fossil fuel has increased throughout the world. Although the increasing use of combustion systems is necessary for industrial development, energy shortages and environmental pollution created by the high energy consumption and increased generation of exhaust gases have become large social issues. Chief among these problems is the level of CO_2 emissions that in 2012, for some representative countries, increased to 293% of the 1990 levels [1]. To reduce the level of CO_2 emissions below the 1990 levels, the current consumption of fossil fuels should be reduced by 75%. Although many researchers have studied renewable energy options to solve the problems of excessive energy consumption and environmental pollution of fossil fuels [2–5], these solutions are expected to require a long period of time to overtake the market, as renewable energy only accounted for approximately 2.9% of total energy consumption in 2012 [6]. Thus, the most effective and economical method to solve the problems of excessive energy consumption and environmental pollution is improving the current fossil fuel combustion systems.

Combustion systems have been used in various ways for industry, transportation and residential and commercial buildings. In 2012 these sectors accounted for 38%, 26% and 34% of the total energy usage, respectively [7]. In industry and in residential and commercial buildings, the combustion system used most often and the one that consumes the most energy is a boiler. A boiler primarily consists of a combustor and a heat exchanger. The heat generated from the combustor is supplied to the heat exchanger via water or steam at high temperatures. The generated heat is supplied to the hot water or heating water used for residential and commercial use or is used in large industrial equipment, such as industrial drying systems. In terms of the most effective and economical approach to solving the problems of excessive energy consumption and environmental pollution, the boiler, which is the most used combustion system in industrial, residential and commercial applications, should be studied to dramatically improve efficiency and reduce pollutant emissions.

Present boilers can be divided into three types: non-condensing boilers (non CB), existing condensing boilers (existing CB) and waste heat recovery condensing boilers (WHR CB). First, non CB only exchanges sensible heat inside the boiler. The exhaust gas

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temperature is approximately 120–160 °C and the efficiency is approximately 82–84%. Existing CB has sensible and latent heat exchangers, providing an efficiency of 86–88% because the exhaust gas temperature is relatively low, approximately 60 °C [8]. Lastly, WHR CB, used in some industrial and residential applications, has a waste heat recovery heat exchanger to recover the waste heat from the exhaust gases in addition to the sensible and latent heat exchangers. WHR CB has approximately 2% higher efficiency than that of existing CB and has the highest efficiency among existing boilers because WHR CB preheats the air supplied to the combustor using the sensible heat of the exhaust gases and the latent heat of the water. Especially, Semkov et al. proposed a simplified method to improve the efficiency through waste heat reduction in industrial systems [9] and Yang et al. presented a new concept of boilers with waste heat recovery for the industrial system, which was achieved the high energy efficiency improvement and great economic benefits [10].

To solve the current energy and environmental problems aggressively, a new boiler needs to be developed with both increased efficiency and reduced pollutant emissions. To achieve this goal, we have studied the effect of exhaust gas recirculation (EGR) on the thermal efficiency and pollutant emission characteristics of various EGR ratios and equivalence ratios [11,12]. In these studies, the EGR method was shown to reduce pollutant emission and increase the boiler thermal efficiency. To further the previous work, we would like to suggest a new boiler: an exhaust gas recirculation-condensed water recirculation-waste heat recovery condensing boiler (EGR-CWR-WHR CB). The EGR-CWR-WHR CB adds EGR and condensed water recirculation, in which the condensed water generated in the exhaust gas is supplied to the preheat air directly to improve the existing waste heat recovery heat exchanger in the WHR CB.

This study includes fundamental research on the development of the new EGR-CWR-WHR CB, which is expected to have a high efficiency and low emission performance. Prior to empirical study, the thermodynamic efficiency of the EGR-CWR-WHR CB was calculated with thermodynamic analysis and compared with other boilers in this study. To achieve this, parameters such as the operating air ratio of the boiler, waste heat recovery performance and the relative humidity of preheated air were considered to calculate the thermodynamic efficiency. Finally, the maximum thermodynamic efficiency of the boiler was obtained using various parameter combinations.

2. Boiler classification and calculation conditions

Figs. 1 and 2 show schematic diagrams of the thermodynamic system for the boilers investigated in this study. In these diagrams, F represents fuel, A is moist air, M is mixture, EG is exhaust gas, CW is condensed water and RG is recirculated gas. The number and character behind each acronym represent each position of the boiler system. For example, the number 1, 2 and 3 behind EG indicate the position just before the main heat exchanger, just after the main body and at the inlet of the WHR device, respectively. Additionally, the lower case e behind EG indicates the final outlet of exhaust gas as the outlet of the WHR and the i behind A indicates the position of the air inlet of the WHR. Here, the composition and properties of moist air at the position of the air inlet of the WHR correspond to the supplied air at ambient conditions. The lower case p indicates the outlet of the preheated and the humidified air from the WHR device.

Fig. 1 shows the schematic diagram of the thermodynamic system for an older boiler. As shown in Fig. 1, the boiler can be divided into the main body and the WHR device. The main body has a combustor and a heat exchanger for the heating water (the main HEX). The WHR device also has a heat exchanger (the WHR HEX) used to preheat the supply air with the waste heat from the exhaust gas exiting the body at EG2. In this study, older categories of boilers were classified as shown in Table 1. The first category divides boilers based on the presence or absence of a WHR device. In the absence of a WHR device, the boiler was classified as either a non CB if it did not condense water during the heat exchange process in the main HEX or an existing CB if it is designed to use the main HEX to condense water. If a WHR device was present, the boiler was classified as a WHR CB. WHR CB has been commercialized partly for industry and is being researched for residential buildings [12]. The WHR CB operates most efficiently when the temperature of the exhaust gas at the boiler outlet (EGe) is lower than the saturation temperature of the water vapor.

Fig. 2 shows the schematic diagram of the thermodynamic system for the new boiler. As shown in Fig. 2, the new boiler adds two further functions to the WHR CB. The first addition is exhaust gas recirculation (EGR) that supplies a portion of the exhaust gas air to the main body by a fan with the venturi function when the air is supplied. The second addition is condensed water recirculation (CWR), which increases the capacity of the waste heat recovery during the preheating process by recirculating a portion of the water in exhaust gas condensed in the process of waste heat recovery into the supply air through the gap of the WHR HEX. The new boiler can be classified by the presence and the absence of EGR and CWR functions as shown in Table 1. EGR-WHR CB only has the EGR function and CWR-WHR CB only has the CWR function, while EGR-CWR-WHR CB has both EGR and CWR functions. Because the boilers listed as new types in Table 1 are not reported yet, they are considered novel concepts for boilers.

Table 1 shows the calculation conditions for the various types of boilers. As seen in Table 1, the air ratio (α), waste heat recovery performance (β) and the relative humidity of preheated air (γ) were the parameters considered for the boilers in this study. In the case of the non CB and the existing CB, the only parameter is the air ratio (α), which is in the range of 1.1–1.4. Typically, the air ratio of a non CB is approximately 1.6, and the air ratio of most existing CB is approximately 1.4, depending on the combustion durability, efficiency and the pollution emission performance [12]. For increased efficiency, the air ratio should approach 1.0; however, when the air ratio goes this low, increasing NO_x emissions and material degradation of the combustor are caused by the increased flame temperature [12]. For the older boilers, the conditions the of exhaust gas at EG2 and EGe are the same, and the conditions of the inlet air at Ai and Ap are also the same. The main parameters of a WHR CB are air ratio (α) and waste heat recovery performance (β), which can be adjusted between 0 and 1. When the waste heat recovery performance is 0, the boiler is not using the waste heat recovery. In this study, the air ratio and waste heat recovery performance of a WHR CB are assumed to be 1.4 and 0.8 to match the existing CB.

For an EGR-WHR CB, the main parameters are the air ratio (α) and the waste heat recovery performance (β). Here, EGR-WHR CB can be used like an EGR CB without WHR, and the main parameter of an EGR CB is the air ratio. Using an EGR CB may be a good way to suppress the NO_x emissions and increase the efficiency because the flame temperature and the NO_x emissions can be controlled by adjusting the air ratio. In this study, the air ratio and the waste heat recovery performance of EGR-WHR CB are assumed to be 1.1 and 0.8. Furthermore, for the CWR-WHR CB and the EGR-CWR-WHR CB, the main parameters are the relative humidity of preheated air (γ), the air ratio (α) and the waste heat recovery performance (β). The air ratios of CWR-WHR CB and EGR-CWR-WHR CB are 1.4 and 1.1, respectively, the waste heat recovery performance is 0.8 and the relative humidity of preheated air is 100%.

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