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Research paper

Development and evaluation of combustion-type CO_2 enrichment system connected to heat pump for greenhouses

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A B S T R A C T

The exhaust gas from combustion has been extensively used for greenhouse CO_2 fertilization. However, its toxic gases and thermal energy would generally limit the proper applicability. The aim of this study is to develop a technology to supply toxic gas-free CO_2 and to recover exhaust gas thermal energy. A combustion-type CO_2 generator was manufactured and connected to a heat pump system for greenhouse heating and cooling. Control algorithm for effective operation of the system was also developed and implemented. Greenhouse operation was run at the conditions under which values for CO_2 concentration and indoor temperature were maintained at 1200–1300 ppm and 25–27 °C, respectively. Technical performance of the system was evaluated in cold, moderate and hot seasons.

1. Introduction

High concentration of carbon dioxide (CO_2) as much as 500–1500 ppm promotes photosynthetic rate. Accordingly, CO_2 enrichment has been stated as a common procedure for improving growth rate, quality and yields of different crops (Hanan, 1998).

The carbon dioxide for CO_2 enrichment is prepared by organic decompositions, chemical reactions, combustion of fuels and pure CO_2, among which, the latter two methods are more facilitative in concentration control. Considering the combustion method for concurrent use of thermal energy in greenhouse heating and provision of CO_2 enrichment, the relevant cost of CO_2 would largely be decreased. In previous studies, Chalabi et al. (2002) compared the economic effects on the applications of pure CO_2 and the CO_2 from natural gas combustion and showed the profitability of combustion method over pure CO_2 procedure. However, the combustion method has some disadvantageous points such as contained toxic gases and high temperature of effluent CO_2 gas. Several researchers have presented methods to resolve the toxic gas problem (Koths, 1964; McKeag, 1965; Hand, 1986; Lugt et al., 1996) and to recover the thermal energy from the combustion using a heat storage tank for further utilizations (Chalabi et al., 2002). Control and monitoring of CO_2 concentration were also among the topics of interest (Kim et al., 1998; Kong et al., 2003; Kläring et al., 2007). Efficiency of CO_2 enrichment is, to a remarkable extent, linked with insulation status and adiabatic conditions of the greenhouse. However, releasing the thermal energy of combustion method's exhaust gas would likely demand for the operation of cooling systems e.g. ventilation devices, which is in discordance with insulation requirements. To overcome this problem and obtain an efficient CO_2 enrichment, some studies have presented methods to maintain the greenhouse insulated and sealed (Willits and Peet, 1987; Schmidt et al., 2008).

In this study, a combustion-type CO_2 enrichment system is developed and integrated with a heat pump system provided for greenhouse cooling and heating purposes. Using the heat exchangers of developed CO_2 generator, thermal energy of the exhaust gas is recovered. Thus, the temperature of injected CO_2 gas would be adjusted to greenhouse indoor temperature. Control algorithm for effective operation of CO_2 enrichment and heat pump system was also developed. Systems were operated and evaluated in cold, moderate and hot seasons.

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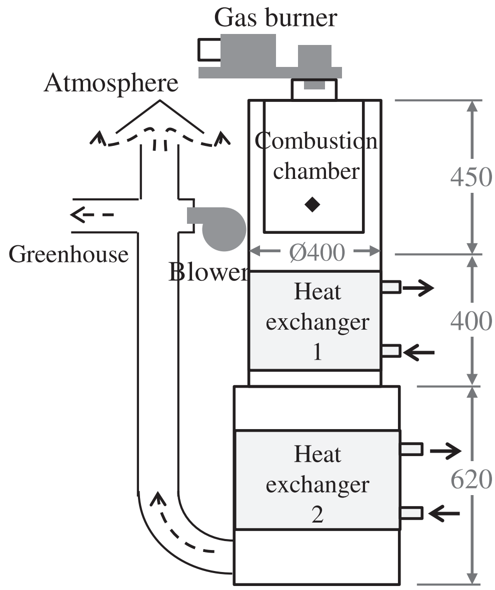

Fig. 1. Structure and dimensions of CO_2 generator. (◆ : temperature sensor point, → : cooling water flow, unit: mm).

2. Materials and methods

2.1. Development of CO_2 generator

As shown in Fig. 1, the developed CO_2 generator consists of a gas burner, a combustion chamber, two heat exchangers and a blower unit. Each component of the CO_2 generator is isolated with ceramic fiber, which keeps its stability up to 1260 °C. The gas burner ignites the LPG in the combustion chamber and the exhaust gas travels to pass heat exchangers 1 and 2 arranged in series. These heat exchangers are designed to drop the temperature of the exhaust gas below 80 °C by circulating water. Blower unit, with a flow rate of 282 m^3/h, blends the exhaust gas with the outdoor air and circulates the mixture to be routed into the greenhouse by the Venturi effect through system's ducts. Mixing the exhaust gas and outdoor air has the dual benefits of adjusting the temperature of injected CO_2 to a point close to greenhouse indoor temperature and dilution of the toxic gases, SO_x and NO_x under non-damaging levels. In case of incomplete combustion, the blower does not operate and exhaust gas is discharged to the atmosphere. Since the CO_2 generator uses the outdoor open air for combustion, plant damage due to oxygen deficiency (Taiz and Zeiger, 1991) is prevented. Fig. 2 shows the manufactured generator.

2.2. Determination of operating condition for toxic gas minimization

The complete combustion is required to minimize toxic gas emissions. The combustion pressure, temperature and air–fuel ratio are the key factors to achieve a complete combustion (Friedman and Johnston, 1950). Because of fixed combustion pressure in the gas burner, complete combustion was controlled through combustion temperature and the air–fuel ratio. Combustion temperature in the combustion chamber was measured using a K-type thermocouple at the position shown in Fig. 1. Air and fuel flow rates were measured using a vane-type airflow meter (VT200, KIMO, France) and a diaphragm-type gas flow meter (G1.6, Shinhan precision, Korea), respectively. The CO concentration of the exhaust gas supplied into the greenhouse was measured using a CO measuring device (ToxiRAE 3, RAE, USA) where a zero CO concentration implied a complete combustion.

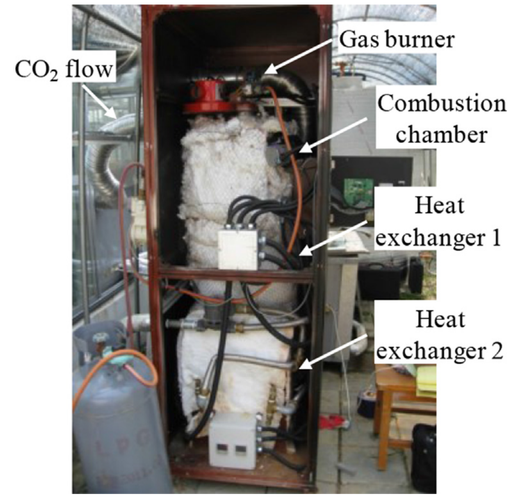

Fig. 2. View of the manufactured CO_2 generator.

2.3. Integrated CO_2 enrichment and heat pump system

The heating and cooling system for the experimental greenhouse involves a heat pump, 10 fan-coil units (FCUs) installed in the greenhouse, an outdoor FCU and heat storage tanks (Fig. 3). The experimental greenhouse is an even-span and double-layered glass house with a floor area of 100 m^2 (6.9 × 14.4 m) and maximum top height of 5.1 m.

The capacity of heat pump and FCUs were 6.5 kW and 0.75 kW, respectively. Nominal volumes of high and low temperature heat storage tanks (HST and LST) were also 5 and 10 m^3, respectively.

The temperature of the cold water in LST, used as circulating coolant in greenhouse FCUs, was maintained at 10–15 °C. Thermal energy stored in the LST moves to HST using the heat pump. Temperature of the hot water in HST, circulated in greenhouse FCUs for heating, was maintained at 35–45 °C. Detailed information on heating and cooling system has been referenced in Yang et al. (2012). The LST is also connected to heat exchangers of the CO_2 generator. Cold water in the LST absorbs the thermal energy generated from the combustion. This energy is either used for heating or discharged to the atmosphere using outdoor FCU.

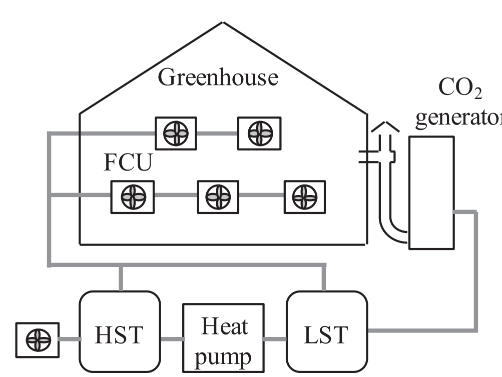

Fig. 3. Schematic diagram of developed CO_2 enrichment system connected to the heat pump.