CO_2 supply to a greenhouse from the combustion of vegetal waste

J.C. López[1,a], J.V. Reinoso[2], M.D. Fernández[1], F.G. Acién[2], J.A. Sánchez-Molina[3], M. David[1], C. Pérez[1] and J.C. Gázquez[1]

[1]Estación Experimental de Cajamar Las Palmerillas, Fundación Cajamar–Grupo Cooperativo Cajamar, 04710 Almería, Spain; [2]Marine Microalgae Research Group. Department of Engineering, University of Almería, 04120 La Cañada de San Urbano, Almería, Spain; [3]Automatic Control, Robotics and Mechatronics Research Group, Department of Informatics, University of Almeria, 04120 La Cañada de San Urbano, Spain.

Abstract

The use of biomass boilers to heat greenhouses is increasing due to the lower biomass cost compared to other fuels such as gasoil or gas. Furthermore biomass fuels are considered environmentally suitable to have a zero balance for CO_2. Moreover, in addition to heat, biomass combustion produces CO_2 that can be used to enhance the production of crops. The aim of this work was to develop a system for recovering CO_2 from the flue gases of biomass combustion and its supply into the greenhouse. The CO_2 capture was performed by adsorption on activated carbon that has the capability of selectively retaining the CO_2 at high pressures and low temperatures. The investigation was carried out at Fundación Cajamar in Almería in a 'parral' greenhouse with an area of 887 m^2. During the daytime hours, the CO_2 greenhouse dose was 9 g CO_2 h^{-1} m^{-2}, and it was necessary to use the heating system for 4 h day^{-1} to capture the CO_2 required. Both the biomass boiler and the CO_2 capture system, resulted in a 2°C increase in air greenhouse night temperature and a mean CO_2 concentration around 600 ppm during the daytime hours. This system can improve yield and reduce CO_2 emissions to the atmosphere with the corresponding environmental benefit.

Keywords: CO_2 enrichment, climate, waste, crop, greenhouse, yield, CO_2 capture, biomass combustion

INTRODUCTION

Agriculture is one of the sectors with greater potential for utilizing renewable energy from sources such as biomass, although it has to be said that crops make treatment of mass and energy flows more sophisticated than in other applications (Boulard and Baille, 1987; IDEA, 2010; Abdel-Ghany and Al-Helal, 2011). Despite this, the presence of other factors such as water consumption, energy requirements, crops, etc., promote the implementation of renewable systems more than in other production environments (Demirbas, 2005). When planning a project to integrate renewable sources in greenhouses the following need to be determined from the outset: (1) The minimum interference conditions on greenhouse production processes by the renewable systems installed and (2) the choice of a self-consumption operation mode, setting the renewable energy production to the specific needs of each farm. In greenhouses, internal temperature control has significant economic importance (Farneti et al., 2013). In the biomass system approach, one of the goals is to reduce the grower´s costs and for this a good system design offers a significant reduction of production cost, as heating represents about 30% of the total (Nachidi et al., 2011). It is also results, therefore, of great interest to increase the efficiency of commercial systems in order to increase the yield (López et al., 2008) and reduce costs associated with heating. In mild climate countries temperature control is performed by convective air exchange between the outside and inside greenhouse (Kläring et al., 2007), which occurs through the windows. In greenhouses, when the photosynthetic rate is high, the CO_2 concentration ($[CO_2]$) falls below

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[a] E-mail: juancarloslopez@fundacioncajamar.com

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the atmospheric concentration producing a deficit. This deficit is even higher when the crop reaches maximum development (Sánchez-Guerrero et al., 2005). Assays performed in Mediterranean greenhouses indicate that the [CO_2] decreases up to 20% compared to atmospheric concentration (Lorenzo et al., 1990), even when the windows are open. As a means of addressing this deficit, some authors propose various carbon enrichment techniques to increase crop production Nederhoff (1995a). Conversely, many authors assert that the photosynthesis rate enhances when increasing [CO_2] above the atmospheric value, from 350-380 ppm to 1,000 ppm. In this range, the photosynthesis rate becomes optimal and cannot be surpassed, even if higher [CO_2] values are used. This photosynthesis rate increase translates into a significant rise in production. Anyway, it is essential to optimize the carbon fertilization strategy, performing them in the absence of other limiting factors. Thus, the best results are obtained when radiation levels are high, then the photosynthesis rate increases with temperature and [CO_2]. Carbon enrichment not only affects the photosynthesis rate, but it also increases the water consumption efficiency by gradually reducing the stomata opening rate, since water loss caused by transpiration decreases (Sánchez-Guerrero et al., 2009).

This work proposes and evaluates a system where CO_2 generated from biomass combustion for heating is captured and stored during the night period to be used during the daylight period. Both, heat and CO_2 are used to increase the yield of crops in greenhouse.

MATERIAL AND METHODS

Greenhouse environment

Experimental data have been obtained from a ‘parral’ greenhouse with a surface area of 877 m^2, a polyethylene cover, and automated ventilation at the Experimental Station of Fundación Cajamar, in El Ejido, in the province of Almeria, Spain (2°43’W, 36°48’N, and 151 m high) (Figure 1). The orientation of the greenhouse was E-W with crop rows aligned N-S. Cropping conditions and crop management was equal to commercial greenhouses. Outside the greenhouse, a meteorological station was installed to measure air temperature, relative humidity, solar radiation, rain, wind direction and speed. During this experiment, the following inside climate variables were also measured: air temperature, relative humidity with a ventilated psychrometer, solar radiation with a pyranometer, as well as [CO_2] and photosynthetic active radiation (PAR) with a silicon sensor. The temperature and humidity air greenhouse were controlled using the windows and the heating system.

Figure 1. Interior of the greenhouse and crop grown for these experiments.

1. Heating system.

The greenhouse was heated using hot water in plastic pipes. A boiler (mod. Missouri, Carsan 150, Spain) with a power of 150 kW was installed with a water accumulation capacity of 300 L with automatic water temperature control, an adjustable pressure air supply for combustion of 200-800 hPa and fuel flow rates from 15 to 80 kg h^{-1}.

2. CO_2 capture and storage system.

The combustion of biomass fuel provided the heating energy requirements. Meanwhile, CO_2 is inevitably produced from this combustion, it being released to atmosphere with flue gases. The boiler operates in accordance with the greenhouse heating demand at night, when minimum temperatures are reached. CO_2 capture and storage is performed using an activated carbon (AC) bed. This material was selected due to its low cost, high capacity for CO_2 adsorption and its ability to perform continuous adsorption-desorption cycles. The useful life is really long, 95% of the original adsorption capacity remaining after five years of operation. The CO_2 used for greenhouse air enrichment was obtained from biomass combustion. The capture and storage system has been previously dimensioned to keep the CO_2 concentration inside the greenhouse above the previously set value. In the assay considered at this work, the injection time was 4 h, taking into account the local weather conditions. Thus, the storage capacity was calculated to fit this specification. With a CO_2 demand of vegetables growing inside greenhouses of 4-6 g CO_2 m^{-2} h^{-1} (Nederhoff, 1995b) and for 1,000 m^2 greenhouse area, storage capacity of 24 kg CO_2 day^{-1} was needed. Nevertheless, it must be kept in mind that CO_2 supply efficiency is usually lower than 100%, so a portion of the CO_2 released into the greenhouse, up to 50%, is lost due to inevitable mass transfer between the exterior and interior of the greenhouse. For that CO_2 storage capacity was designed for 36 kg day^{-1}. It was estimated that on most days it would be possible to keep the greenhouse ventilation closed for 4 h. When other usual greenhouse problems, like diseases (*Botrytis cinerea,* etc.), related to excess air humidity and dripping of condensation from the cover, occurred the windows were opened. In addition, the difference between exterior and interior temperatures and air relative humidity was carefully followed because some other kind of problems can also be given if this event takes place (relative abrupt changes of these variables can facilitate the appearance of micro- cracking in fruits). The CO_2 adsorption capacity of the AC employed was 24 g CO_2 kg^{-1} AC at the operating conditions, therefore it was required that 1,500 kg of AC were employed for the system used in this work, in order to provide the 36 kg CO_2 day^{-1} requirement previously explained. It only was possible to achieve this CO_2 capacity by working at pressure higher than the atmospheric (2 bar) and getting the gas temperature as lower as possible (close to ambient temperature, around 20°C). The pressure was created by using a medium pressure range blower. The flue gas temperature was reduced by placing two heat exchangers between the gases leaving the boiler and AC tank (Figure 2). The flue gas was cooled by natural convection. The heat exchangers consisted of tubes with external fins. The flue gas was circulated through these tubes. Lowering the flue gas temperature was also required to meet the specifications of the blower.

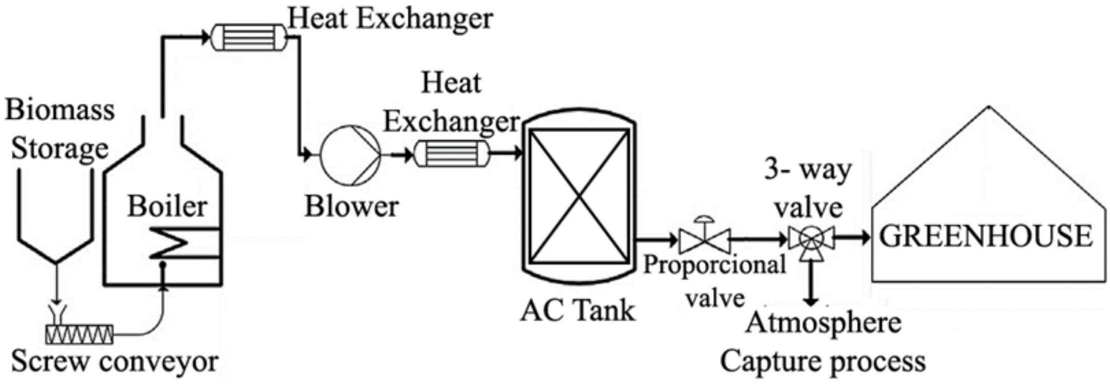

Figure 2. Block diagram of the heating and CO_2 capture system employed.

The use of AC for this application is interesting, since this material is a selective adsorbent of CO_2, thus using this material it is possible to capture CO_2 from flue gas, removing other toxic gases also generated from biomass combustion (CO, NO_X, SO_X). The CO_2 absorption capacity of AC is based on Van der Walls interactions between molecules, this also explain its CO_2 selectivity, considering that the polarity of this molecule is higher than the other toxic gases from which CO_2 need to be extracted. The process of the CO_2 recuperation system had three steps: (1) CO_2 capture from flue gases; (2) purification of CO_2, removing other toxic gases also generated from biomass combustion, mainly CO, NO_X and SO_X and (3) supplying of CO_2 to the greenhouse only when it is demanded. Capture and supply procedures, use the same actuator, a proportional valve set after the tank. During capture, the AC tank pressure can be measured using pressure sensors located in the outlet and inlet tank pipes; meanwhile, this pressure is controlled using a valve placed on the tank outlet. Flow and CO_2 sensors were also added to provide complementary process information. After the tank valve and the CO_2 concentration and flow sensors, there is a three-way valve. This valve is quite important for the system development, since it allows the choice of where the gas stream coming out the tank is released, either inside or outside the greenhouse. If CO_2 capture is in progress, then the gases are directed to the outside, since the aim of this process is to capture selectively the CO_2, hence the stream would be rich in CO, NO_X and SO_X. The mentioned sensors (CO_2 concentration, gas flow and tank pressure) were also used for controlling the CO_2 released during its supply. The composition of gases (CO, CO_2, O_2, SO_x, NO_x) at four different points in the system (chimney, AC tank, gas pipes and air greenhouse) was measured using flue gas analyzers (IM 1400 Environmental Equipment and RAE MultiRaeLite).

RESULTS AND DISCUSSIONS

CO_2 capture and storage system

The time period when heat was demanded by the temperature control system was longer than that required to store the CO_2 required for CO_2 enrichment during the day. Minimum temperatures are more often given during night, just after sunrise. The time period required to completely saturate the AC bed of CO_2 was between of 3 h. The CO_2 concentration available in the flue gas stream from the chimney was 7% vol. The saturation AC bed status could be easily followed with the CO_2 concentration of the capture system. The AC bed was saturated when the CO_2 concentration values was close to the 7% value present on flue gas (Figure 3).

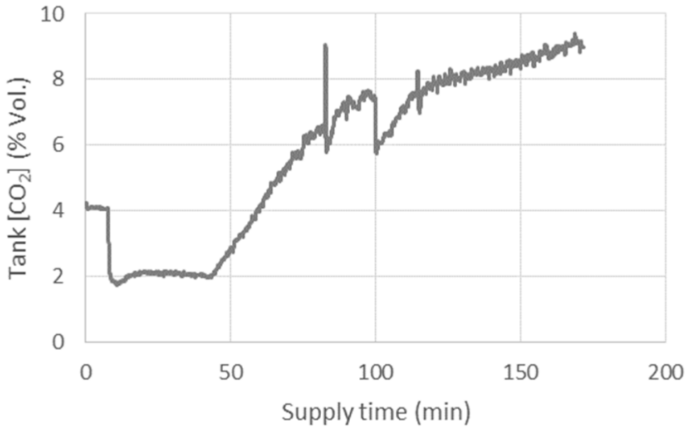

Figure 3. CO_2 measured in AC tank during the CO_2 capture process from gas stream.

The variables monitored for the CO_2 capture control strategy were [CO_2] of gases leaving the AC tank, flue gas temperature, temperature of the gases leaving the heat exchanger between the boiler and the blower, and the available solar radiation. In order to maximize the process efficiency, it was necessary to start CO_2 capture only when biomass combustion was in progress and flue gas [CO_2] was stable and as higher as possible (around the 7% value previously stated). Experimentally, it was observed that, for optimum boiler working conditions, the flue gas temperature was around 200°C (Figure 4). These two values were taken as references for the control strategy, CO_2 capture did not start until [CO_2] was higher than 5.25% (75% the maximum possible value). At the other hand, [CO_2] was also employed to follow the saturation status of the AC bed. Once this concentration value becomes higher than 5.25%, it implies that AC bed saturation level is a 75% its capacity. Therefor CO_2 capture wasn't started if this saturation value was reached when heating was demanded because of economic criteria.

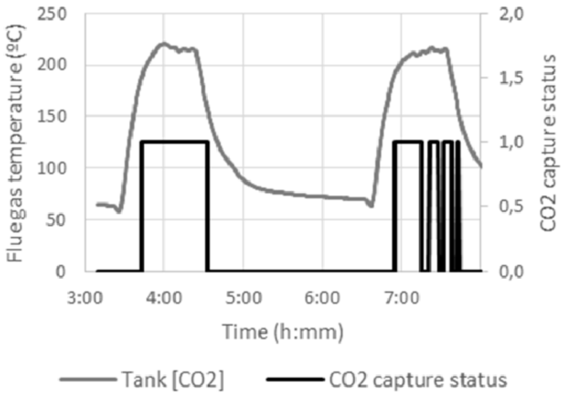

Figure 4. Progress of flue gas temperature followed in order to monitor the biomass combustion status during CO_2 capture. CO_2 capture axis: 0 means off and 1 means on.

The other key variable for the control of the process is the flue gas temperature. In addition to these two control variables, also the AC saturation status was taken into consideration. As it has been stated before, if AC reached the 75% its saturation capacity, the amount of CO_2 captured was enough to ensure the supply into the greenhouse for 4 hours the next day, according to the system design. In addition, beyond this 75% saturation capacity, CO2 capture efficiency notably decrease. Thanks to this CO_2 supply, it was possible to keep the CO_2 concentration of the greenhouse environment higher than its atmospheric value during 3 h and higher than 600 ppm (Figure 5). In the middle time, temperature and relative humidity did not excess critical values related with the growing conditions of tomato plants (Figure 6).

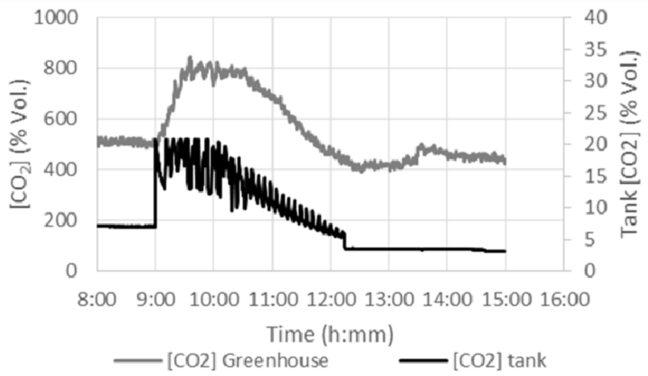

Figure 5. CO_2 supply in greenhouse and CO_2 gas stream coming from AC tank.

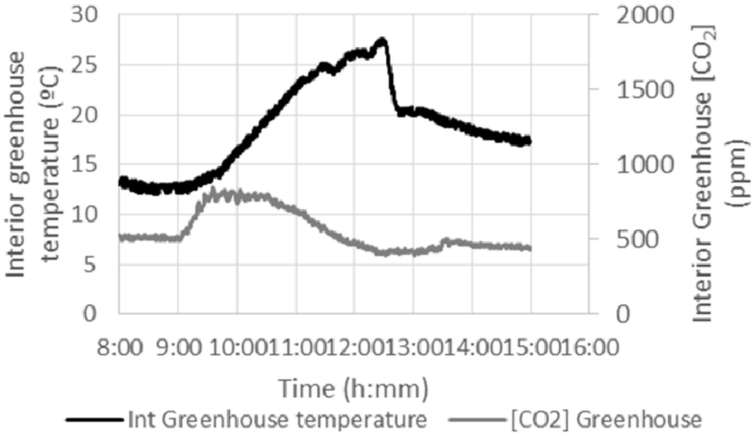

Figure 6. Greenhouse air temperature during the CO_2 supply with closed vents.

Toxic gases removal

Measuring the concentration of toxic gasses (CO, NO_X and SO_X) in different points of the system, made it possible to demonstrate that the AC bed allows some removal of CO gases from the CO_2 supply. The concentration of this gas at the inlet of the AC bed was higher than at the outlet. This observation was in accordance with the theoretical assumptions, regarding results obtained (Table 1), it is possible to tell that affinity of the AC bed for these gases is lower than that for CO_2.

Table 1. Toxic gasses concentration (ppm) present in several parts of the system.

PLACE	CO	NO	NO_2	NO_X	SO_2
Chimney	1244	-	-	38,5	0,0
AC Tank during CO_2 capture	1034	-	-	0,0	0,0
AC Tank during CO_2 supply	>500	0	1,1	1,1	>20,0
Pipe distribution holes in greenhouse	347	0,0	0,0	0,0	7,6
Greenhouse environment	5	0,0	0,2	0,2	0,2

At the other hand, the low concentration of NO_X and SO_2 detected for the gas stream coming out the tank during the CO_2 supply points out that AC also has better affinity for CO_2. The additional measurements performed to determine the concentration of these gases at the greenhouse environment corroborate this observation. These values were below the ones beyond them, the first drawbacks for plant growing start to take place.

The CO concentration in the tank during the supply process and in pipe distribution holes indicates that this gas is partially retained in the AC bed, but when it is released to the greenhouse the final concentration is very low due to the dilution of gas with the air inside the greenhouse (4,000 m^3). Regarding the NO_X concentration, the values measured at different points (chimney, tank, pipe and greenhouse) are similar and much lower than measured for SO_2 concentration. In fact the concentration observed at the chimney is lower than the one observed in the AC tank outlet during CO_2 supply can be explained because of the wider measurement range of the flue gas analyzer and the fact that this concentration is quite low in the case of this study.

CONCLUSIONS

A capture and storage system for recovering CO_2 from flue gases, during the combustion of biomass for heating to incorporate it into the greenhouse, was developed and evaluated. Both, biomass boiler and CO_2 capture system provided an increase in the temperature of the air inside the greenhouse of 2°C at night period and a CO_2 concentration of 600 ppm during the daylight time. This system can increase greenhouse crops yield and reduce CO_2 emissions to the atmosphere with the corresponding environmental benefit.

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