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Biomass combustion for greenhouse carbon dioxide enrichment

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ABSTRACT

Greenhouses in northern climates have a significant heat requirement that is mainly supplied by non-renewable fuels such as heating oil and natural gas. This project's goal was the development of an improved biomass furnace able to recover the heat and the CO_2 available in the flue gas and use them in the greenhouse. A flue gas purification system was designed, constructed and installed on the chimney of a wood pellet furnace (SBI Caddy Alterna). The purification system consists of a rigid box air filter (MERV rating 14, 0.3 μm pores) followed by two sets of heating elements and a catalytic converter. The air filter removes the particulates present in the flue gas while the heating elements and catalysers transform the noxious gases into less harmful gases. Gas analysis was sampled at different locations in the system using a TESTO 335 flue gas analyzer. The purification system reduces CO concentrations from 1100 $cm^3\ m^{-3}$ to less than 1 $cm^3\ m^{-3}$ NO_x from 70 to 5.5 $cm^3\ m^{-3}$ SO_2 from 19 $cm^3\ m^{-3}$ to less than 1 $cm^3\ m^{-3}$ and trapped particulates down to 0.3 μm with an efficiency greater than 95%. These results are satisfactory since they ensure human and plant safety after dilution into the ambient air of the greenhouse. The recuperation of the flue gas has several obvious benefits since it increases the heat usability per unit biomass and it greatly improves the CO_2 recovery of biomass heating systems for the benefit of greenhouse grown plants.

1. Introduction

The benefits of greenhouse crop production is widely documented and recognised as a valuable technique to produce food throughout the year. In addition to the control of the ambient temperature, a greenhouse allows the producer to control a variety of other parameters influencing plant growth. The greenhouse can control humidity, temperature, air circulation, water and nutrient cycles, lighting intensity and duration, and the concentration of carbon dioxide in the ambient air [1]. The effects of carbon dioxide concentration inside the greenhouse have been extensively studied in the last two decades in order to determine the optimum level for improved growth of different plant species [2]. Table 1 summarizes the benefit of CO_2 enrichment for different species of plant.

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Table 1 – Review of the effect of CO_2 enrichment on the growth enhancement of different plant species [2].

Observations	Growth enhancement
All herbaceous plants	+45%
Woody plants	+48%
Herbaceous populations	+29%
Woody populations	+35%
Dry Matter productions	+20%
Grassland biomass	+12%
Forest Growth	+23%

In general, greenhouse enrichment to CO_2 concentrations between 700 and 900 $cm^3\ m^{-3}$ is valuable regardless of the plant species [3]. Some species experience growth reduction and leaf injuries for concentration higher than 1000 $cm^3\ m^{-3}$ [3]. Humans have higher tolerance to carbon dioxide where no adverse effects are observed for concentrations lower than 7000 $cm^3\ m^{-3}$ [4]. As a safety precaution, the Canadian Ministry of Health recommends that individuals should not be exposed to a concentration greater than 3500 $cm^3\ m^{-3}$ [4].

The current popularity of biomass furnaces for greenhouse heating allows for a new source of CO_2 for greenhouse producers [5]. The utilisation of the CO_2 produced during combustion of biomass for greenhouse enrichment has great advantages for producers since it reduces producers' environmental footprint and their dependency on fossil fuels which are typically used for enrichment [5]. However, the utilization of the CO_2 from the flue gas of a wood pellet furnace presents considerable challenges due to the presence of different noxious gases (CO, NO_x, SO_x, C_2H_4, etc) and particulates. Thus, the aim of this research project was to improve a biomass furnace in order to recover the heat and the CO_2 that is typically vented with the flue gas and release them into the greenhouse.

2. Flue gas composition

Flue gas composition varies greatly in function of the type of biomass, the dimensions of the pellet, puck or briquette, and the type of stove/furnace used for the combustion [6]. The oxygen to fuel ratio determines the emission composition during combustion. The expected emissions of different types of stoves/furnaces are summarized in Table 2 [6]. In general, pellets stoves produce less noxious emissions than other stove types because the shape of the biomass allows a good distribution of oxygen which produces a uniform and complete combustion. Consequently, pellets stoves flue gas is easier to purify and therefore more suitable for greenhouse CO_2 enrichment. The combustion of all types of biomass results in the production of air-borne pollutants. The most important noxious gases found in the flue gas are CO, NO_x, particulates, SO_x, and VOCs [5]. It is also common to find trace amounts of nitrous oxides (N_2O), hydrogen chloride (HCl), heavy metals (Cu, Pb, Cd, Hg), polycyclic aromatic hydrocarbons (PAH), polychlorinated dioxins and furans (PCDD/F), ammonia (NH_3) and ozone (O_3) [6].

2.1. *Carbon monoxide (CO)*

Carbon monoxide (CO) is the product of incomplete combustion of carbonaceous fuel into CO_2. Thus, CO concentration in the exhaust gases is a good indicator of the quality of the combustion [6]. Control of the CO formation can be achieved mainly through the adjustment of the air to fuel ratio at a stoichiometric level in the combustion chamber. In fuel lean conditions, more CO will be formed due to improper mixing conditions and lack of oxygen to oxidize CO into CO_2. In fuel rich conditions, more CO will be formed in consequence of the reduction of temperature in the combustion chamber caused by the excess oxidizer reactant [7]. Increasing the residence time will also contribute to reduce the concentration of CO in the emission [8].

It has been reported that a CO concentration of 30–50 $cm^3\ m^{-3}$ can be detrimental to plants and cause leaf chlorosis and abscission as well as flower drop [3]. Also, CO can negatively affect human health at concentrations lower than those previously mentioned. Indeed, inhaled CO molecules diminish blood ability to carry oxygen to cell and tissues [5]. Thus, an exposure of no more than 10 $cm^3\ m^{-3}$ of CO during 24 h is recommended [4].

2.2. *Nitrogen oxides (NO_x)*

Nitrogen oxides are produced by three main gas phase reaction mechanisms during the combustion process. First of all, there is the fuel NO_x mechanism. The nitrogen present in the wood is volatilized during the combustion process to create NH_3 and HCN molecules [9]. Depending on the fuel type, the oxygen level, the temperature in the combustion chamber and the residence time, different NH_3 to HCN ratio will be produced. These molecules are subsequently converted into NO and NO_2 according to a series of elementary reactions [9]. Nitrogen oxides are produced by the thermal NO_x mechanism. At temperatures higher than 1300 °C, nitrogen in the air reacts with oxygen molecules creating NO [6]. An increase in NO concentration in the flue gas is generally the result of an augmentation of temperature, oxygen concentration and residence time in the combustion chamber. Lastly, NO_x are

Table 2 – Arithmetic average emission levels in mg m^{-3} at 13% O_2 from small-scale biomass combustion applications [6].

Appliances	Load [kW]	Excess air ratio	CO [mg/m³][a]	C_xH_y [mg/m³][a]	Particles [mg/m³][a]	NO_x [mg/m³][a]	Temp [°C]	Efficiency [%]
Wood-Stoves	9.33	2.43	4986	581	130	118	307	70
Fireplace inserts	14.07	2.87	3326	373	50	118	283	74
Heat-storing stoves	13.31	2.53	2756	264	54	147	224	78
Pellet stove	8.97	3.00	313	8	32	104	132	83

[a] The term m^{-3} designates a volume at standard reference condition; pressure 101.3 kPa and temperature 273 K.

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