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Thermodynamic Analysis of Superheated Steam and Flue Gas as Drying Agents for Biomass Dryers

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Bagasse is a sugarcane byproduct of high moisture content that usually requires drying before its use in the production of heat, power, fuels, and chemicals. This work explores the possibility of replacing flue gas, a hazardous heat source, with steam in bagasse rotary dryers using Aspen Plus v8.6 as a simulation tool. In the simulation, a bagasse-fed combined heat and power (CHP) plant generated superheated steam at 2 bar and flue gas, and both acted as drying agents in zero-dimensional biomass dryers that reduced bagasse moisture from 50 to 10 wt.%.The biomass final moisture content is inversely proportional to the drying agent temperature and flow rate. Steam dryers required a steam-to-wet-biomass ratio (S/WetBiom) of 4.0 with 2-bar steam at 260 °C to achieve a steam-to-evaporated-moisture (S/EvapMoist) ratio of 9.0, which is suggested for steam as a drying agent. For flue gas dryers, the equivalence ratio (ER) played an essential role: higher ERs increased the O_2 content in flue gas, reducing the gas higher heating value (HHV), and increasing the amount of flue gas required per unit of evaporated moisture (FG/EvapMoist). Thus, ER values of 1.1 were advised to counterbal-ance the effects of ER and still provide enough excess air to allow complete fuel combustion in the CHP furnace. As the flue gas exiting the furnace presented extremely high temperatures (~1550 °C), this stream was cooled down to the superheated steam temperature (260 °C), and drying performances were compared. Although flue gas had an HHV lower than the steam latent heat, it presented higher production yields, resulting in lower bagasse combustion requirements in the CHP to provide enough drying agent per kg of dried biomass in flue gas dryers. Nevertheless, if the CHP system adopts steam split ratios in the range of 0–0.2 and alternative steam sources are available in the biorefinery, steam can be an attractive drying medium for biomass dryers.

1. Introduction

Renewable energy sources such as biomass residues have received growing interest due to the need to diversify the energy and chemicals market (Leal Silva et al., 2018; Marchesan et al., 2019). In this context, the sugar-alcohol industry produces solid wastes such as bagasse in the milling of sugarcane, which can be used as a raw material to produce fuels, chemicals, heat, and electricity owing to its availability and high calorific value in comparison to other biomass sources. However, sugarcane bagasse drying is usually required prior to most processing routes as it commonly presents 50–60 wt.% moisture contents (Motta et al., 2018).

Biomass drying is a necessary stage in biorefineries (Verma et al., 2017), as high moisture levels affect the feeding, performance, and energy efficiency of the downstream equipment such as burners and reactors. Also, the high heat demands of biomass dryers may affect a plant heat integration and result in high capital costs, in a way that biomass drying should be carefully studied (Brammer and Bridgwater, 2002).

Biomass dryers in Brazilian biorefineries typically operate with hot flue or exhaust gases from furnaces and combustors as drying media (Fagernäs et al., 2010). Nevertheless, flue gases are non-environmentally friendly, presenting fire hazards due to their high temperatures and large mass flow requirements to ensure drying (Swanson et al., 2010). Superheated steam could act as a substituent, providing an inert atmosphere during start-up and shutdown, as well as lower temperatures and emissions of contaminants (Fagernäs et al.,

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2010). However, little experience in bagasse drying using steam has been found, and new superheated steam dryer applications require their proper analysis for future design (Mujumdar, 2014).

This work explores the possibility of replacing flue gas with steam in bagasse drying from 50 to 10 wt.% using Aspen Plus v8.6 as a simulation tool. In this paper, superheated steam and flue gases were produced at a bagasse-fed combined heat and power (CHP) system at different operational conditions, and the effects of the properties of each drying medium on drying performance and fuel consumption in the CHP plant are assessed.

2. Materials and Methods

2.1 Simulation

In this work, a biomass dryer and a CHP plant were simulated in Aspen Plus v.8.6. Figure 1 presents the simulation flowsheets, and Table 1 describes the simulation blocks and streams.

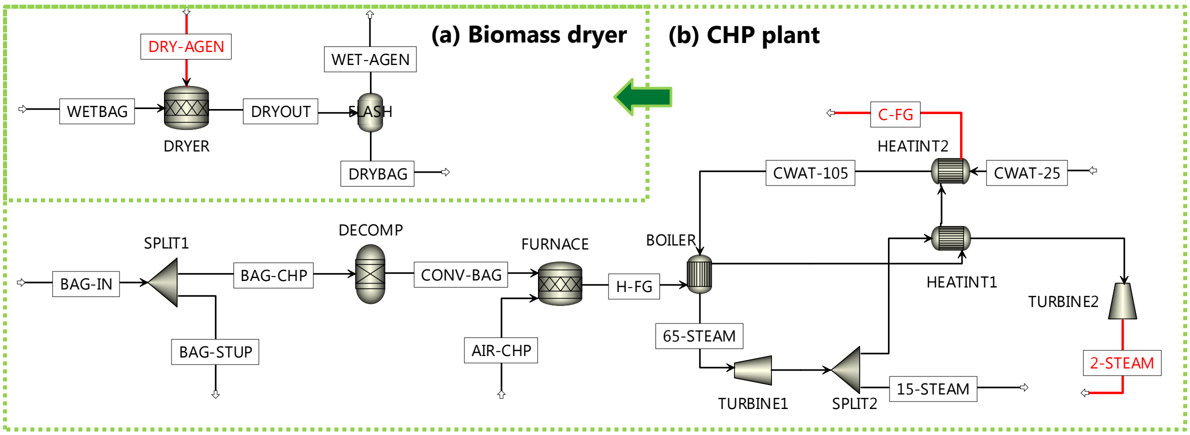

Figure 1: Simulation flowsheets of (a) biomass dryer (b) and CHP plant.

*Table 1: Description of streams and blocks in the simulations. DS: design spec specified throughout the text, ER: equivalence ratio, HP: high-pressure, LP: low-pressure, MP: medium-pressure, ^{NC}: nonconventional stream, P: pressure, X: conversion, *base case, assumes values of 0–0.4 in the analysis of steam split ratios.*

Stream	**Description**	**Stream**	**Description**
2-STEAM	LP steam, 2 bar, 140–400 °C/260 °C	CWAT-105	Cold water, 65 bar, 105 °C, mass flow: see DS
15-STEAM	MP steam, 15 bar, 292.16 °C	CONV-BAG	Similar to BAG-CHP, used for CHP start-up
65-STEAM	HP steam, 65 bar, 485 °C	DRY-AGEN	C-FG or 2-STEAM
AIR-CHP	Air, 1 bar, 25 °C, ER = 1.0–1.2	DRYBAG^{NC}	Dry bagasse, ~100 °C, 10 wt.%
BAG-CHP^{NC}	Wet bagasse for furnace, 1 bar, 25 °C, 50 wt.%	DRYOUT	Mixture of DRY-AGEN and WETBAG
BAG-IN^{NC}	Wet bagasse total feed, 1 bar, 25 °C, 50 wt.%	H-FG	Hot flue gas, 1 bar, T depends on ER
BAG-STUP^{NC}	Wet bagasse for start-up, 1 bar, 25 °C, 50 wt.%	WET-AGEN	DRY-AGEN containing removed moisture
C-FG	Cold flue gas, 1 bar, 260 °C	WETBAG^{NC}	Wet bagasse for drying, 1 bar, 25°C, 50 wt.%
CWAT-25	Cold water, 65 bar, 25 °C, mass flow: see DS		
Block	**Description**	**Block**	**Description**
BOILER	HEATX, cold outlet stream: 485 °C	HEATINT1	HEATX, cold outlet stream: 503 °C
DECOMP	RYield, 1 bar, 25 °C	HEATINT2	HEATX, cold outlet stream: 105 °C
DRYER	RStoic,1 bar, adiabatic, X depends on final MC	SPLIT1	Splitter, 0.05 split ratio for BAG-STUP
FLASH	Flash, 0-bar P drop, adiabatic	SPLIT2	Splitter, 0.2* split ratio for 15-STEAM
FURNACE	RStoic, 0-bar P drop, adiabatic, combustion	TURBINE1,2	Turbines, isentropic efficiency of 85%, discharge P of 15 and 2 bar, respectively,

As bagasse, flue gases, and steam were the main components in the simulations, the Peng-Robinson with Boston Mathias modifications equation of state as well as STEAMNBS tables were used for calculations. Also, the proximate and ultimate analyses of sugarcane bagasse were extracted from de Medeiros et al. (2017).

The biomass dryer (Figure 1a, based on AspenTech, 2013) is a zero-dimensional equipment that dries bagasse at ambient conditions from 50 (WETBAG) to 10 wt.% (DRYBAG) using superheated steam at 2 bar (2-STEAM) or flue gas (C-FG), both at 260 °C. The flue gas composition depends on the equivalence ratio (ER) adopted on the CHP plant, that is, the mass flow ratio between the air fed to the CHP furnace and the stoichiometric air for complete combustion. For example, an ER of 1.1 produces a flue gas stream composed of 12.5% CO_2, 26.7% H_2O, 59.6% N_2, and 1.3% O_2 (vol. basis). The biomass dryer consists of a DRYER block, which converts part of the moisture of the non-conventional WETBAG into a conventional component (evaporated moisture), and FLASH, which separates the evaporated moisture from the sugarcane bagasse stream. Some of the conditions of the CHP plant (Figure 1b) were based on the work of Morais et al., 2016. The CHP contains the blocks DECOMP, which is setup by a calculator block to convert BAG-CHP into the conventional stream CONV-BAG; FURNACE, which burns the wet bagasse (CONV-BAG), generating hot flue gas (H-FG); BOILER, HEATINT1, and HEATINT2, which consist of three heat integration blocks for hot flue gas (H-FG) cooling and steam generation (65-STEAM), steam (15-STEAM) heating so that 2-STEAM is at 260 °C after expansion, and heating of cool water from 25 (CWAT-25) to 105 °C (CWAT-105), respectively; and TURBINE1 and 2, which generate medium (15-STEAM) and low-pressure (2-STEAM) steams, respectively. The turbines discharge pressures of 15 and 2 bar were chosen based on the steam pressures required by some pressurized gasifiers (Motta et al., 2019) and for the steam dryer, respectively. Two splitters were setup to save part of the bagasse input for the CHP plant start-up (SPLIT1) and part of 15-STEAM (SPLIT2) for use in a gasifier. The simulation considered a fixed bagasse fuel mass flow (BAG-IN) of 1000 kg/h, and the mass flows of some streams were determined via design specs: the mass flow of WETBAG was varied to obtain a moisture content of 10 wt.% in DRYBAG, while the mass flow of CWAT-25 was varied so that C-FG temperature was 260 °C.

2.2 Analysis of parameters

This work analyzed (i) the influence of superheated steam temperature (140–400 °C) and steam/wet biomass flow ratio (S/WetBiom, 2–14) on the dryer performance; (ii) the effect of ER (1.0–1.2) onto the flue gas properties and dryer performance for a fixed steam split ratio (0.2) in SPLIT2; and compared (iii) steam and flue gas productions, as well as the bagasse input (stream BAG-IN) in the CHP system to generate the drying agents required to obtain 1 kg of 10 wt.% bagasse, using varying steam split ratios in SPLIT2 (0–0.4).

3. Results and Discussion

Biomass dryers are necessary upstream of many biochemical and thermochemical processes since high moistures reduce the temperature of reactors, as part of the energy is diverted to dry the feed. Specially, wet feedstocks reduce the cold gas efficiency and affect the product composition of most thermochemical processes (Motta et al., 2019). Thus, the following passages analyze whether superheated steam can be a feasible substituent of flue gas in the drying of sugarcane bagasse to avoid such undesirable effects.

In steam dryers, four parameters are essential: the steam temperature (T_{steam}), the steam-to-wet-biomass ratio (S/WetBiom), the steam-to-evaporated-moisture ratio (S/EvapMoist), and the biomass final moisture content (MC_{out}). Precisely, S/WetBiom and S/EvapMoist are of utmost importance because they show the steam feed in relation to the wet biomass feed and the evaporated moisture, respectively.

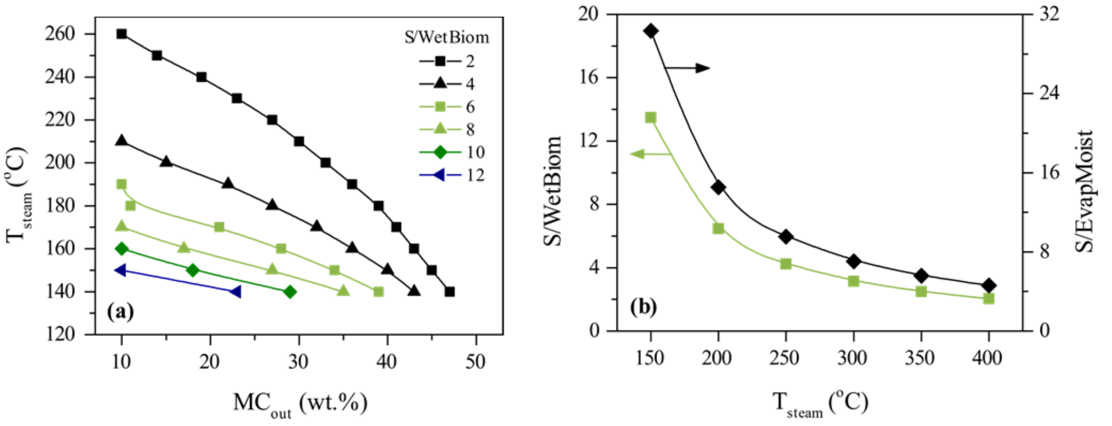

Figure 2: Relationships between (a) T_{steam} and MC_{out} for varying S/WetBiom, and (b) T_{steam}, S/WetBiom, and S/EvapMoist for a 10 wt.% MC_{out}.

Figure 2a shows that different combinations of T_{steam} and S/WetBiom are inversely proportional to MC_{out} and that different combinations of T_{steam} and S/WetBiom can produce distinct bagasse moistures. For a fixed MC_{out} of 10 wt.%, Figure 2b illustrates that T_{steam} has an inverse relationship with S/WetBiom and S/EvapMoist, like other experiences with different biomass sources and drying agents (Zabaniotou, 2000). For example, superheated steam at 150 °C requires S/WetBiom and S/EvapMoist of 13.5 and 30.3, respectively, while a 400 °C temperature requires much lower ratios of 2.1 and 4.6 for the same parameters, respectively.

Considering steam dryers usually operate at S/EvapMoist near 9.0 (Swanson et al., 2010), the conditions at which a steam dryer must run to dry bagasse from 50 to 10 wt.% MC are S/WetBiom of 4, T_{steam} of 260 °C, and pressure of 2 bar. Such conditions are close to the ones used by Swanson et al. (2010) to dry corn stover from 50 to 12 wt.% with superheated steam.

The CHP plant was then simulated to produce low-pressure steam at the conditions required for bagasse drying, adopting a steam split ratio of 0.2 in SPLIT2 (see Figure 1) and varying ER from 1.0 to 1.2. As an illustration, the CHP plant produces 1.64 and 1.61 kg of 2-bar steam/kg of burned bagasse with ERs of 1.2 and 1.0, respectively. For an S/WetBiom of 4.0, then 4.4 (ER = 1.0) and 5.6 (ER = 1.2) kg of wet bagasse must be burned in the CHP system to generate enough steam to obtain 1 kg of bagasse containing 10 wt.% moisture at the outlet of the steam dryer. This considerable amount of bagasse fuel demonstrates why biomass drying is one of the biorefinery areas with the highest heat demands (Fagernäs et al., 2010).

Figure 3 reports the main results of the flue gas produced in the CHP system at varying ERs. Figure 3a shows that increasing ERs reduce the flue gas temperature at the exit of the furnace (stream H-FG), as a result of the excess air that does not react and thus dilutes the produced flue gas.

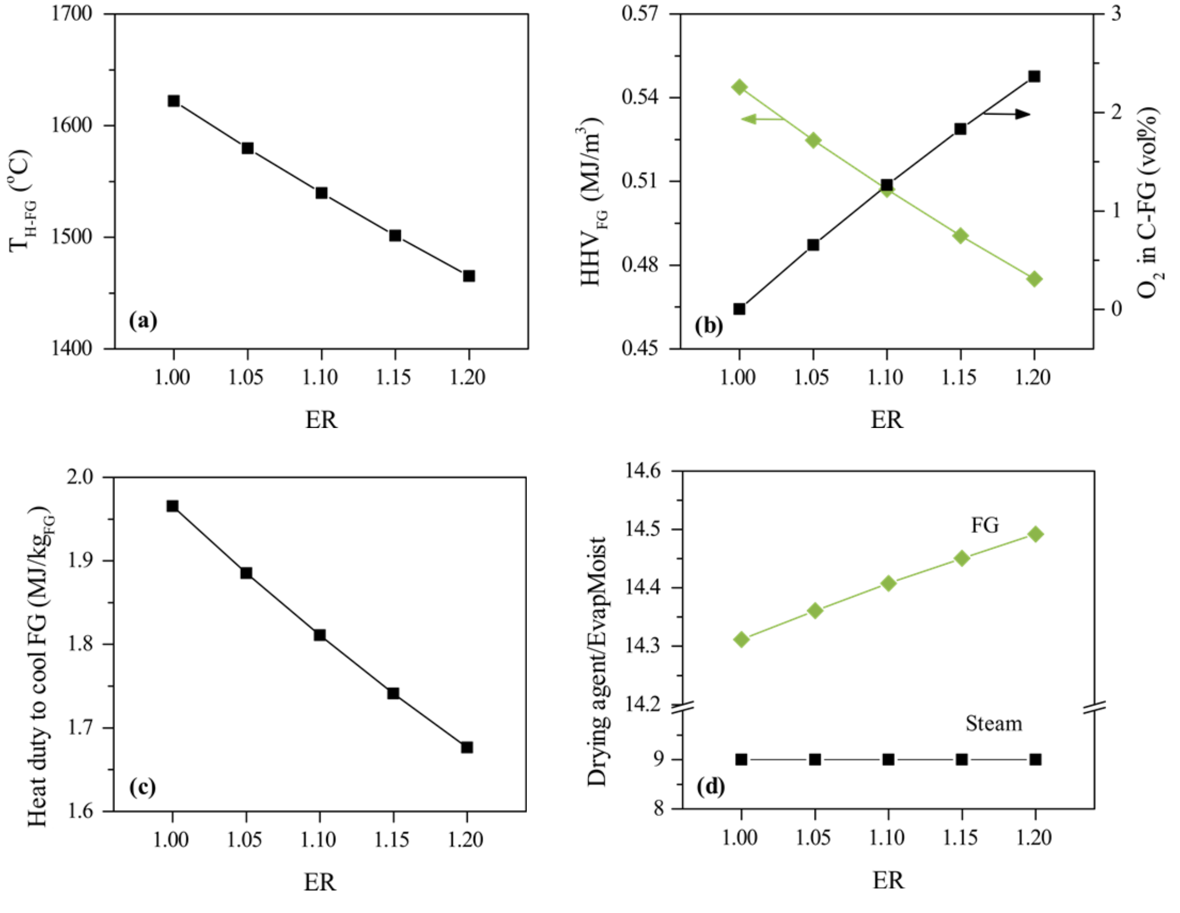

Figure 3: Effect of ER on flue gas parameters for a fixed steam split ratio of 0.2: (a) hot flue gas temperature outside the furnace (stream H-FG, T_{H-FG}); (b) flue gas HHV and O_2 content; (c) heat duty required to cool stream H-FG down to 260 °C; (d) and drying-agent-to-evaporated-moisture ratios for flue gas and superheated steam.

Figure 3b reinforces the dilution effect of ERs, as higher ERs increase the O_2 concentration in the exhaust gas from 0 to 2.4 vol.% and reduce the gas higher heating value (HHV). The oxygen contents in the flue gas are below 8 vol.%, the maximum limit of oxygen concentrations that drying media must have not to impose severe fire or explosion risks (Fagernäs et al., 2010). Despite the acceptable O_2 levels, the high temperatures of the hot flue gas stream (H-FG) ranging from 1465 to 1622 °C still represent a hazard due to the risk of spark development through slow pyrolysis and smoldering (Fagernäs et al., 2010). Therefore, Figure 3c shows the heat duty requirements to cool the hot flue gas (H-FG) down to 260 °C before use as a drying agent. The selection of the 260 °C temperature for flue gas was driven to facilitate the comparison of steam and flue gas dryers, and because it stands in the typical operating range for flue gas rotary dryers (250–400 °C) (Fagernäs et al., 2010). The heat duty comprises the contributions of the blocks BOILER, HEATINT1, and HEATINT2 per kg of flue gas. The heat duty (Figure 3c) is inversely proportional to ER similarly to temperature (Figure 3a), as higher ERs result in lower flue gas temperatures and, thus, smaller driving forces for heat exchange.

Figure 3d compares the drying performance of superheated steam and flue gas both at 260 °C. Steam dryers require smaller drying agent mass flows per amount of evaporated moisture than flue gas, which is due to the higher latent heat of steam (Swanson et al., 2010). While steam shows an S/EvapMoist of 9.0 as determined previously, flue gas presents FG/EvapMoist of 14.3–14.5, illustrating the lower hazards of steam as a drying agent as it requires lower flow rates than flue gas to dry the same amount of bagasse. FG/EvapMoist slightly increases with ER (Figure 3d), as a result of the negative effect of ER on the flue gas HHV (Figure 3b).

In the analyzed ER range, an ER value must be selected for the final CHP system. ERs equal to 1.0 should be avoided because some excess air may be demanded to guarantee complete combustion in the furnace, and because low ERs produce flue gases at too high and hazardous temperatures above 1600 °C (Figure 3a). However, high ERs such as 1.2 are not advantageous either, as they result in high air consumption and lower HHVs (Figure 3b). Therefore, CHP systems must run at an intermediate ER of 1.1.

For an ER of 1.1 in the CHP system, Figure 4 shows the effect of varying steam split ratios on the drying agents production in the CHP plant and consumption in the biomass dryers.

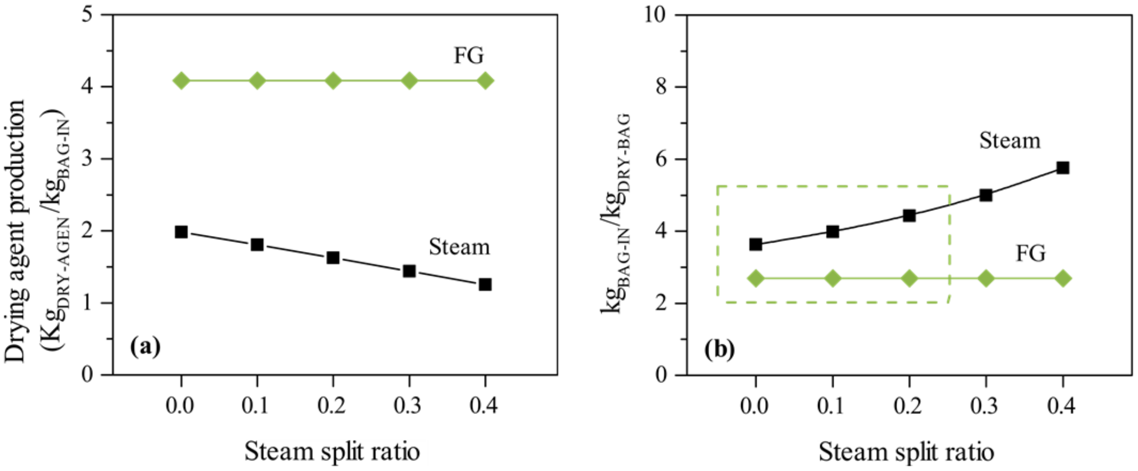

Figure 4: Influence of SPLIT2 steam split ratio on (a) drying agents production per kg of bagasse fed to the CHP plant (stream BAG-IN; and (b) bagasse consumption (BAG-IN) to obtain 1 kg of dry bagasse (DRY-BAG) for either steam or flue gas dryers.

Figure 4a shows that the same bagasse fuel feed to the CHP system produces more flue gas than steam. The flue gas production is constant as it occurs before the steam split, in a way that 4.1 kg of flue gas is produced per kg of burned fuel. On the other hand, 2.0–1.3 kg of superheated steam is produced per kg of bagasse fuel with steam split ratios in the range of 0–0.4. Therefore, higher steam split ratios decrease the relative amount of low-pressure steam produced.

Finally, Figure 4b shows the balance between the heating capacity and production yields of each drying agent in the form of bagasse fuel consumption in the CHP per kg of dried bagasse in the biomass dryer. Although superheated steam presents a higher calorific value than flue gas as indirectly demonstrated in Figure 3d, the lower levels of steam production in comparison to flue gas resulted in higher bagasse consumption per kg of dried biomass for steam dryers than for flue gas dryers. The overall bagasse consumption in steam dryers increases with higher steam split ratios, as more bagasse needs to be burned to produce enough low-pressure steam for the same drying conditions. Nevertheless, steam drying is comparable to flue gas drying if the CHP plant adopts steam split ratios in the range of 0–0.2, as such split ratios resulted in the lowest fuel consumption differences between both drying agents. In case processes other than gasification require medium-pressure steam (e.g.: steam reforming), the fuel input must be increased to account for this additional demand, which can be achieved with the use of other agricultural residues available at the biorefinery like sugarcane straw. Also, higher steam split ratios can be used if bagasse is dried to a much lesser extent (achieving moisture contents above 10 wt.%) and if alternative steam sources are explored in the biorefinery heat integration framework. For example, thermochemical plants produce high-temperature syngas that requires cooling before syngas cleaning and conditioning and could work as a heat source for steam generation. These alternate scenarios show that steam drying can be performed in a flexible manner to explore the environmentally friendly and low-hazards features of this drying agent.

4. Conclusions

Sugarcane bagasse dryers usually operate with flue gases as drying media, which can be hazardous agents due to their very high temperatures, large mass flows, and possible emissions of dangerous gases into the atmosphere. In this context, this work assessed the technical feasibility of using superheated steam as a drying agent in substitution of flue gases in the drying of sugarcane bagasse from 50 to 10 wt.% moisture content. A combined heat and power (CHP) plant produced both superheated steam and flue gases and was designed according to the desired properties of such drying agents. Biomass steam dryers must operate with 2-bar superheated steam at 260 °C and S/WetBiom ratios of 4.0 to dry bagasse from 50 to 10 wt.%. The same biomass moisture content can be achieved with the use of flue gas at 260 °C, 0.51 MJ/m^3 heating value, FG/WetBiom of 6.1, and produced in a CHP running with ER of 1.1. Although superheated steam presents a higher calorific value than flue gas, steam dryers require higher fuel consumption in the CHP per kg of dried bagasse than flue gas dryers. Nonetheless, steam drying is comparable to flue gas if the CHP system adopts steam split ratios in the range of 0–0.2. Also, alternative CHP fuels like straw and steam sources in biorefineries can be used to provide superheated steam to the steam dryer. This paper has shown that bagasse drying can take place under more environmentally friendly and safe conditions with the use of steam as a drying agent.

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