Fuel Processing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

A modelling approach for the assessment of an air-dryer economic feasibility for small-scale biomass steam boilers

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ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 24 January 2015
Accepted 31 January 2015
Available online xxxx

Keywords:
Biomass
Moisture
Air-drying
Small-scale
Feasibility

ABSTRACT

Fuel drying is an energetically and economically expensive pretreatment process, which may not be worth the investment in the case of small-scale generation plants. This paper presents an investigation on the air dryer feasibility to enhance the operation of biomass steam boiler. In the proposed approach, the external drying technology using preheated air and the biomass steam production system is modelled in terms of energy and an economical analysis. A focus is given to the system size influence on the dryer economic suitability: the smallest size of the biomass combustion system for which fuel drying is a suitable solution, from the economic point of view, is computed. In the computations, the heat used for drying is assumed to be part of the cost for operating the dryer and the thermal balance of the system is assumed to be previously verified. According to the model results, if the steam production plant operational time is above 8000 h/y, wood chips drying is feasible if the system size is larger than 1.78 t_{daf}/h of fuel processed.

1. Introduction

1.1. Technical context

The biomass feedstock for energy production often contains a high moisture fraction: freshly cut biomass can include up to 65%$_{w,wb.}$ (percentage on weight, on wet fuel basis) moisture when harvested, depending on the type of biomass and the environmental conditions.

External (or surface) moisture is the moisture fraction above the equilibrium moisture content and it generally resides outside the biomass cell walls. Inherent moisture, on the other hand, is absorbed within the cell walls. When the walls are completely saturated, the biomass is said to have reached the fibre saturation point, or equilibrium moisture [1]. The fibre saturation point increases with the relative humidity of external air and lower temperatures (Fig. 1) [2]. In wet and cold climates, the inherent fuel moisture might be as high as 30%$_{w,wb.}$ [2]. As a consequence, open air drying is not effective. Despite unforeseeable climate conditions (and logistical problems) leaving wet biomass outdoors can have at times a positive effect concerning moisture [3]. Biomass materials are also hygroscopic; even dried and stored, they can still absorb moisture from the atmosphere, until the equilibrium moisture content is reached [3,4].

In most cases active drying is a necessary pre-treatment process related to the technologies of thermal conversion of biomass: a high moisture content decreases the efficiency of the energy conversion, since the moisture must be first evaporated. To guarantee combustion quality, some industrial boiler technologies require the minimum low heating value (LHV) of biomass fuel to be above 15 MJ/kg$_{wb.}$ [3]. Moreover, the auto-thermal and self-supporting combustion limit, for most biomass fuels, is around 65%$_{w,wb.}$ of water content [5,6].

If the fuel moisture fraction is below the auto-thermal self-supporting combustion limit, drying is not necessary for combustion (in grate furnaces), but results in demonstrated benefits [1,3,4,7], such as:

- Increased and homogenised fuel LHV, with a decrease in the requirements for the combustion air pre-heating and process control.
- Increased flame temperature, hence a potential increase in the steam production in existing facilities. According to Van Loo [3], if the biomass fuel is dried from a moisture content of 50%$_{w,wb.}$ to 30%$_{w,wb.}$, the boiler thermal efficiency can potentially be improved by 8–10%. A lower air excess ratio may also be used if a more complete combustion is reached thanks to the higher temperature.
- In existing combustion facilities, a decrease in the amount of flue gases passing through the boiler (smaller emissions control equipment) and lower product gas velocities (potential decreased erosion). In case of a new plant design, smaller heat exchange surfaces are needed (decreased boiler dimensions).

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http://dx.doi.org/10.1016/j.fuproc.2015.01.043
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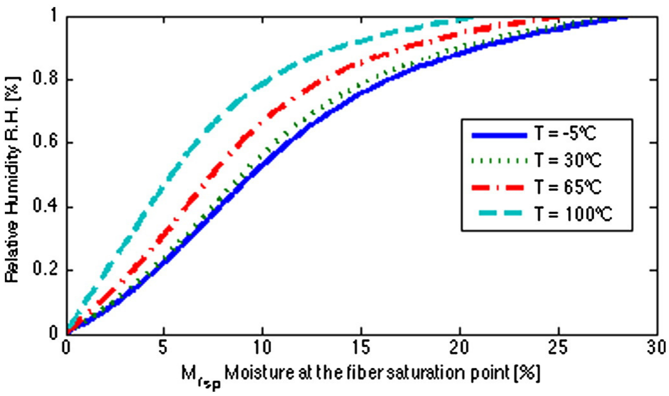

Fig. 1. Equilibrium moisture content of wood as a function of relative humidity and temperature (moisture at the finer saturation point), computed using the correlations proposed in the Wood Handbook [2].

- In case of long term storage, reduced risk of biological contamination problems.

These potential advantages are counterbalanced by numerous issues [4,5,8–10]:

- Dryers have a relatively high investment cost, which largely impacts small-scale plants. Globally, though the boiler thermal efficiency increases, the costs savings remain moderate [3]. Moreover, drying is an energy intensive operation.
- Explosions could occur and fires might arise if fuel ignition is reached during drying operation. Fire protection systems are necessary, increasing the system investment costs.
- The dryer effluents have to be treated as exhaust gases or as wastewater discharges.
- Burning very dry biomass (e.g. $<10\%_{w,wb.}$) may increase the *CO* and the total particulate emissions [11]. Furthermore, the boiler operational temperatures, if increased, can approach the fusion temperature of some of the fuel ash constituents, increasing the slagging risk.
- If the boiler is designed for processing dry fuel and the dryer fails, the boiler becomes undersized for burning wet fuel. A backup low-moisture fuel may be needed.
- Wet fuels can be utilized in grate combustion boilers, by increasing the combustion air preheating (e.g. 300–350 °C) or by means of proper Flue Gas Recirculation (FGR). However, grates capable of handling high combustion air temperatures, advanced air preheaters and excellent refractories are necessary [4].

Additionally, the use of different drying media determines benefits and concerns (Table 1). Looking at the dryer energy efficiency and energy integration in the plant, flue gas drying and steam drying are to be preferred. However, with respect to air drying, both technologies might have lower capacity and control characteristics.

The use of low-enthalpy flue gas to dry the fuel is usually the less expensive solution, but fuel ignition is a risk in presence of sufficient oxygen and high temperature [12,14]. Air drying is the most flexible solution and the process efficiency can be improved using multistage drying [15]. Steam drying is sensitive to the material size and size uniformity and, in general, despite the low heat specific consumption (kJ per kg of water evaporated), is more expensive. In case of superheated steam dryers, the latent heat of vaporization and the water is easy to recover and treat because the water vapour is not diluted with air [14]. Finally, the drying technology can be chosen (e.g. rotary dryers, belt dyers, flash dryers), taking into account that each technology has specific technical limits (e.g. the operating temperature) [14,16–19].

In conclusion, the choice of drying or not the fuel for power production is not a trivial task. In case of larger biomass combustion units (above 30 MW_{th}) it has been experienced that it is worth paying the investment for a feedstock dryer to improve the steam production efficiency. A moisture content of $35\%_{w,wb.}$ is a trade-off between the enhanced combustion performance and the increased capital cost [20]. The trade-off between the dryer investment and the operating costs on one side, and the enhanced boiler efficiency on the other side, in case of small-scale distributed combustion systems is seldom explicitly studied in the literature.

Table 1
Multi-criteria analysis for different drying media available [8,11,12]. Configurations where different drying media are coupled are also commercially available.

	Air	Steam	Flue gases
Energy efficiency and heat integration	−	+	+
Dryer effluents[a]	−	+	+
Fire and explosion risks	−	+	−
Fuel size flexibility	+	−	+
Control and capacity	+	−	−

[a] Dryer emissions depend also on the biomass type [13].

1.2. Literature review

Brammer and Bridgwater [21] focused on the influence of feedstock drying on systems coupling a small-scale biomass gasifier and an internal combustion engine. The minimum cost of electricity produced was determined incorporating a rotary dryer with a burner, drying from an initial moisture content of $50\%_{w,db.}$ (percentage on weight, dry basis) to a final moisture content of $10\%_{w,db.}$. The highest overall energy efficiency was obtained with drying to a final moisture content of $35\%_{w,db.}$.

Gebreegziabher et al.'s [9] approach was to maximize the annual profit of the operation of the dryer for biomass combustion, without modelling the steam plant. The optimum solution indicated that the dryer subsystem is profitable with the moisture level of the dried wood at $17\%_{w,wb.}$. Moreover, when the size of the wood chips becomes too large, the drying time is too long, thus significantly increasing the dryer size and energy cost.

Ho Ting Luk et al. [10] investigated how drying affects the overall energy efficiency of a 12.5 MW biomass power plant that burns Empty Fruit Bunch (EFB), a feedstock with $60\%_{w,wb.}$ moisture, to support proper heat integration between the dryer and the power plant. In their study, two types of dryers (which have different operating temperatures), a Hot Air Dryer and a Superheated Steam Dryer, are proposed for the drying process. With proper heat integration, the overall efficiency of the production plant could be improved by about 5% when compared to process without drying. The economical aspects of drying were not investigated.

In [13], H. Li et al. presented the results of a model of a belt conveyor drying system for pine wood chips at $60\%_{w,wb.}$ inlet moisture content, with flue gas and steam as drying agents, that could provide dried fuel to a 40 MW plant. While using flue gases as the heat source for drying, the dryer capital cost computed was about €2.5 million; while using superheated steam, the capital cost was about €3 million, because of the higher quality steel in the equipment. The evaluation of the dryer profitability was performed defining a fuel-selling price, after the dryer, without modelling the successive energy conversion. At a dried fuel selling price of 14 €/MWh, 3–4 years of operation was expected to give a return on the initial dryer investment.

H. Holmberg and P. Ahtila in [22,23] have compared the exergy efficiencies and the drying costs (capital and operational) of two types of drying systems: single-stage drying with partial recycle of spent air, and multi-stage drying. According to the results, the irreversibility production depends to a considerable extent on the heat source and the drying system. The single-stage drying is usually more economic when the amortisation time is short. However, the competitiveness of multi-stage drying improves as the amortisation time becomes