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Minimization of total drying costs for a continuous packed-bed biomass dryer operating at an integrated chemical pulp and paper mill

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ABSTRACT

This paper presents a MILP (Mixed Integer Linear Programming) model for a continuous packed-bed biomass dryer. The model minimizes total drying costs, including both capital and operational costs, of the dryer. Heated air, which flows through a biomass bed and perforated conveyor, is used as drying gas by the dryer. We define the dryer size with the help of an experimentally-measured characteristic drying curve. The MILP model is tested in a case study where the dryer is assumed to have been installed at a Scandinavian pulp and paper mill. There are three different heat sources available for the heating of drying air: warm water at 60 °C, warm water at 80 °C and backpressure steam at the pressure of 0.4 MPa. The results indicate that, in practice, the use of only low-temperature warm water flows for heating of drying air is the most economic method when their prices are low (below 1 € MWh^{-1} in the case study). Warm water flows are usually waste heat from pulp and paper mills and their prices are low compared to the price of back-pressure steam (typically from 10 to 15 € MWh^{-1}). The use of steam for drying may be reasonable if the price of warm water is for some reason clearly higher than the price of a typical waste-heat stream. The MILP model presented in this work can be used for minimizing drying costs of any material (not only biomass) dried in a continuous packed-bed dryer if the characteristic drying curve of the material is available.

1. Introduction

Solid wood-based biomass, such as bark, forest residues and saw dust, is usually obtained as by-products from manufacturing processes of mechanical and chemical forest industry. Here, the mechanical forest industry means mills where lumber and wood-based panels are produced. Traditional chemical forest industry mills produce paper, paper board and pulp. It is not unusual that there are both chemical and mechanical forest industrial production units at the same mill site.

Typical moisture content of biomass varies between 50% and 65% wb, depending on the biomass type, season and weather [1]. Most of the biomass is combusted in fluidized bed boilers at the mill site, but potential emerging conversion technologies are intensively developed to utilize the energy content of biomass in more effective and environmentally

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Nomenclatures

a	evaporation surface of the bed per bed volume, $m^2\ m^{-3}$
A_D	cross sectional area of the dryer, m^2
A_H	surface area of the heat exchanger, m^2
c_{el}	electricity price, € MWh^{-1}
c_{fuel}	fuel price, € MWh^{-1}
c_{heat}	heat price, € MWh^{-1}
c_p	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
c_{steam}	steam price, $€^{-1}\ MWh^{-1}$
C_{inv}	investment costs, €
C_{op}	operational costs, €
e	specific exergy content, $J\ kg^{-1}$
h	specific enthalpy, $J\ kg^{-1}$
k	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
l_v	vaporization heat of water, $J\ kg^{-1}$
m	number of mass ratio steps
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
$\dot{m}_o^{'}$	constant drying rate over the bed per dry solid of the bed, $kg\ s^{-1}\ kg^{-1}$
n	number of heat sources, –
M	molecular mass, $kg\ mol^{-1}$
Δp	pressure difference, Pa
P	power consumption, W
R	gas constant, $J\ mol^{-1}\ K^{-1}$
s	entropy, $J\ kg^{-1}\ K^{-1}$
T	temperature, K
t	temperature, °C
Δt_{ln}	logarithmic mean value temperature, °C
U	relative mass ratio of water to dry solids, –
u	mass ratio of water to dry solids, $kg\ kg^{-1}$
u_{cr}	critical mass ratio of water to dry solids, $kg\ kg^{-1}$
Δu	mass ratio step, $kg\ kg^{-1}$
v	air velocity per cross-sectional area of the dryer, $m\ s^{-1}$
$\dot{V}$	volume flow rate of dry air, $m^3\ s^{-1}$
wb	water mass fraction in the material, $kg\ kg^{-1}$
x	absolute humidity of air, $kg\ kg^{-1}$
Z	bed height, m

Greek symbols

α	average heat transfer coefficient per evaporation surface of the bed, $W\ m^{-2}\ K^{-1}$
β	annuity factor, –
ε	power-to-heat ratio of the CHP plant, –
Φ	heat consumption, W
γ	pumping cost factor, –
η_{CHP}	total efficiency of the CHP plant, –
η_{fan}	efficiency of the fan, –
ρ	bulk density, $kg\ m^{-3}$
δ	density, $kg\ m^{-3}$
τ	time, s
τ_{op}	annual operational hours of the dryer, h

Subscripts

da	dry air
db	dry bulb
ds	bone-dry solid
H_2O	water
in	inlet/ingoing
m	material
o	environment, reference state
out	outlet/outgoing
v	vapor
wb	wet bulb

friendly ways, for example to produce electricity through Integrated gasification Combined Cycle (IGCC) [2–4] or new value-added end-products from biomass such as liquid traffic fuels [5] or synthetic natural gas (SNG) [6,7]. Mills producing new value-added products are usually called biorefineries and also form part of the chemical forest industry. In most conversion processes, biomass must be gasified before further processing. The moisture content of biomass should be between 10 and 15% wb in gasification, which means that biomass drying is a necessary unit process before gasification. Fluidized bed boilers usually combust biomass without any pre-drying, but the high moisture content decreases the energy-efficiency of the power plant.

There are both low-temperature waste-heat streams and steam available to heat the drying air at forest industry mill sites. Waste heat streams usually have their origin in heat recovered from various process effluents or cooling processes to water flows. Typically, temperatures of waste-heat streams range from 40 °C to 90 °C [1]. Steam pressures usually vary between 0.3 MPa and 1.5 MPa, depending on the mill. Waste heat streams are cheaper than energy steam, but, due to low-temperature level, the air demand in drying increases. This means higher capital costs than in the use of steam. Higher air demand also increases electricity consumption of the fans. Preliminary design of the biomass drying configuration at the forest industry mill site is a classic optimization problem: low operational costs mean high capital costs and vice versa.

In several studies, biomass drying is not optimized as a separate unit process but is studied as a part of optimization problems of larger energy systems, such as dryer and power plant system [8–10], dryer-gasifier and CHP engine system [11] and biomass-based fuel production processes [5,6]. An extensive review of the most promising drying technologies of wood-based biomass and optimization of these technologies for an integrated bioenergy plant is given in Ref. [12]. A 15% improvement in energy-efficiency is reported when a single-stage zeolite drying process and an adsorber-regenerator heat recovery system are optimized simultaneously using the pinch-analysis [13].

Optimization of the entire energy system is usually a good approach because sub-optimization can be avoided. On the other hand, optimization of a large energy system means that simplifications must be carried out when sub-processes are modeled. By creating more detailed models, some researchers have also optimized single dryers. Design parameters of conveyor-belt dryers for food drying have been optimized in Refs. [14,15]. In Ref. [16], total drying costs (including both capital and operational costs) for heat-pump fruit dryers, have been minimized. Drying of wood-based biomass in packed