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Pretreatment of recycled paper sludge with a novel high-velocity pilot cyclone: Effect of process parameters on convective drying efficiency

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HIGHLIGHTS

- A low-temperature cyclone was set-up for processing challenging sludge materials.
- Sludge dry solids content and specific energy consumption were modeled.
- Efficient drying can be achieved with inlet air temperature levels $\geqslant 40\,^{\circ}C$.
- Data show significant findings for the use of secondary energies in sludge drying.

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ABSTRACT

To address the growing need for economically viable sludge processing technologies and associated resource recovery, a novel convective high-velocity pilot cyclone was set-up at the Swedish University of Agricultural Sciences in Umeå, Sweden. In essence this process entails feeding ($\leqslant 900$ kg h^{-1}) a material to a heated high-velocity air flow (approx. 13×10^3 m^3 h^{-1}) allowing moisture removal at low temperatures. This equipment is expected to improve drying of challenging industrial sludge materials when used as a pretreatment method prior to further processing. Modeling results based on an experimental campaign on recycled paper mill sludge indicated that efficient drying with a specific energy consumption of $\leqslant$1–1.2 kWh kg^{-1} H_2O can be achieved with inlet air temperature levels $\geqslant 40\,^{\circ}C$ coupled with respective feeding capacity of $\leqslant 750$ kg h^{-1}.

1. Introduction

Traditional forest industries are facing increasing waste disposal problems due to regulations aimed at conserving the environment. Despite of the significant progress that has been made during recent years in reducing related environmental impacts [1], the need for effluent treatment processes make these industries one of the leading generators of inorganic and organic semi-solid and solid wastes [2–4]. Although the favored management option for disposal of primary and secondary (or even tertiary) wastewater treatment sludge has been incineration in solid fuel boilers or evaporation in recovery boilers, the low total solid and high ash contents of these residuals still prompt reliance on alternative disposal options.

Within the pulp and paper industry, the quantities and chemical composition of sludge streams depend on the paper grade being produced, specific fresh water consumption, applied wastewater treatment technique and the types of raw materials used in production [1,5]. Wastewater treatment processes generally consist of mechanical primary treatment by, e.g., gravity settling followed by secondary treatment using chemical or biological methods [1,4,6]. In the case of paper recycling, recycled fibers are potentially deinked depending on the characteristics of the raw material and subsequently pulped after which residual fibers unsuitable for further utilization are separated.

In order to reduce the volume and to increase the effective heat value of generated wastewater treatment sludge materials, economically and environmentally viable methods for increasing the total solids content are of key concern. Sludge dewatering is generally managed by centrifuges, filters or various pressing machines, which however are unable to remove intracellular and chemically bound water present in the sludge suspensions [6,7]. Hence, although mechanical dewatering has been seen as

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Nomenclature

A, B, C	liquid specific constants for the Antoine equation
C_p	specific heat capacity, kJ kg^{-1} °C^{-1}
DSC	dry solids content, %
d.w.	dry weight
E	energy efficiency of drying, kWh kg^{-1} H_2O
MC	moisture content, %
m	air mass, kg h^{-1}
NTP	normal temperature (20 °C) and pressure (101,325 kPa)
p	absolute pressure, kPa
Δp	differential pressure, kPa
p_s	saturated vapor pressure, kPa
p_v	vapor pressure, kPa
Q	heat energy, MJ h^{-1}
Q^2	predicted variation of a model
R^2	explained variation of a model
SS	sum of squares
T	temperature, K
t	temperature, °C
W	power input (fan motor), kW
X	moisture in material, kg H_2O kg^{-1} (d.w.)
Y	absolute moisture in air, kg H_2O kg^{-1} (d.w.)
ρ_A	air density, kg m^{-3}
φ	relative humidity, %

Physical constants

M_A	molar mass of air, 28.9645 g mol^{-1}
M_W	molar mass of water, 18.01 g mol^{-1}
R	universal gas constant, 8.3144621 J mol^{-1} K^{-1}
R_A	specific gas constant of air, 2.870699×10^{-1} J g^{-1} K^{-1}
R_W	specific gas constant of water, 4.616581×10^{-1} J g^{-1} K^{-1}

Subscripts and superscripts

A	air
a	accept
f	feed
fan	fan
HA	humid air
ia	inlet air
pre	prediction
res	residual
sh	sensible heat
tot	total
V	vapor
W	water
0	ambient

the most energy efficient way for removing large quantities of water from sludge suspensions, mechanically dewatered sludge can, depending on sludge type and dewatering unit, only reach maximum dry solids contents of 18–50% [8]. In addition, secondary sludge is generally far more difficult to dewater than primary sludge and thus most facilities dewater a mixture of primary and secondary sludge [4]. The main drawback of incinerating mechanically dewatered sludge is a low net calorific value of 2–6 MJ kg^{-1} compared with the net calorific value of, e.g., bark (7 MJ kg^{-1}) and black liquor (12 MJ kg^{-1}) which are the predominant biofuels in pulp and paper mills [8]. A selection of thermal drying systems can be used for the removal of intracellular and chemically bound water from sludge suspensions, with attainable dry solids contents of nearly 95%, but conventionally result in an exponential increase in the respective energy consumption of drying operations [9–11].

To address the growing need for viable sludge handling practices and respective resource recovery, novel low-temperature drying methods suitable of utilizing the potential secondary energies of industrial environments are required. Hence a pilot-scale high-velocity cyclone was set up at the Biofuel Technology Centre at the Swedish University of Agricultural Sciences in Umeå, Sweden. Similar efforts in the field of sludge drying under high air velocities have been presented by, e.g., Hayashi and Shimada [12] and Lee and Cho [13] in laboratory and pilot scales, respectively. This particular technology, currently not industrially applied, has previously been discussed by Tikka et al. [14] in the context of metals industry residues, and by Lähdeniemi et al. [15] in drying deinking sludge from pulp and paper mill operations. However, in the latter contribution the authors emphasized that none of the relevant process parameters were optimized during experimentation as the authors reported only the results of a single preliminary experiment excluding data on specific energy consumption of drying. This contribution aims to continue that work by presenting detailed results from our first pilot-scale low-temperature drying and optimization campaign processing recycled paper mill sludge from a local liner paper mill.

2. Materials and methods

2.1. Description of the pilot set-up

The dryer pilot set-up is located in Umeå, Sweden (61°81′33″N, 21°23′97″E) and is centered around a convective cyclone, Fig. 1, where sludge drying can be performed at low temperatures enabled by a high-capacity (13×10^3 m^3 h^{-1}) electrical fan run by an electric motor. The feed material (approx. capacity ⩽900 kg h^{-1}) is fed to the inlet air stream and the air-material suspension directed to the cyclone (approx. height 4 m) where changes in pressure and radial velocity induce water vaporization and possible particle grinding and separation phenomena [14]. In the current set-up the inlet air stream can be heated to ⩽90 °C through the combustion of wood chips/pellets in a heating unit. The bulk of the dried material (accept fraction) is recovered from the bottom of the cyclone while the fine particles (reject fraction) are captured from the humid exhaust air stream in a separate baghouse filter unit (Fig. 1). A slit inside the cyclone is used to control the flow distribution to the filter unit. Material sampling from the exhaust air stream, performed with a separate small-scale filter, is used to avoid sample contamination in the filter unit. Real-time data logging of relevant fan power input, temperature, relative humidity and absolute and differential pressure values ensure the acquisition of relevant process data.

2.2. Feed material

A recycled paper sludge stream from a regional pulp and paper mill was processed during the experimental campaign. This specific mill uses virgin sulfate (240,000 t a^{-1}) and recycled fiber (200,000 t a^{-1}) pulp for the production of 435,000 t a^{-1} unbleached kraft/eurokraft liner for corrugated cardboard. Once the recycled paper is received at mill it is subsequently pulped and washed with the reject fibers separated by pressure sieves and screw presses thus generating a recycled paper sludge stream. Fresh sludge samples were received weekly during the campaign and stored in a