Fuel Processing Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Research article

Energy-efficient fluidized bed drying of low-rank coal

Yuping Liu *, Hiroaki Ohara

Chemical Engineering Department, Products Development Center, IHI Corporation, 1, Shin-Nakahara-cho, Isogo-ku, Yokohama, Kanagawa 235-8501, Japan

ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form 3 June 2016
Accepted 11 June 2016
Available online xxxx

Keywords:
Drying
Energy-saving
Freezable water
Non-freezable water
Fluidized bed

ABSTRACT

An energy-saving and economical process was developed for drying low-rank coal using steam as the drying medium. Based on simulation tests, the energy consumption of the process was found to be nearly 30% lower than that of vapor recompression drying. The proposed process involves the removal of the freezable water in the coal in an exergy recuperative module, while the non-freezable water is removed in a heat integration module. During the removal of the freezable water, the evaporated water is compressed to a low pressure and recycled to the fluidized bed dryer for heat exchange with the incoming coal to minimize exergy destruction. Conversely, medium-pressure steam extracted from a steam turbine is used as the heat source for the removal of the non-freezable water. No compressor was used in the process which significantly reduced the capital cost. Moreover, technical feasibility has been verified through investigating the fluidization performance of the low-rank coal particles in the fluidized bed dryer during the proposed process, particularly to determine the effect of the increased heat exchange tubes on the fluidization performance.

1. Introduction

Low-rank coal (LRC) deposits are globally dispersed and currently account for approximately 50% of the world's coal reserves [1]. The increased utilization of high-rank coal (HRC) in recent times has significantly depleted the reserves of such coal and the exploitation of LRC is expected to grow in the near future. LRC has the advantages of higher reactivity and lower sulfur content. However, it also has some disadvantages such as higher transportation cost and lower calorific value, which necessitates the use of larger boilers to achieve the same thermal output as HRC. The lower caloric value of LRC is mainly due to its higher water content of 45–66 wt% (wet basis (wb)). Water in LRC exists on the surface and in the pores. It occurs in the form of freezable water on the surface and macropores and non-freezable water, which is chemisorbed by interaction with polar residues in coal particles. Freezable water can be removed with slightly superheated steam and drying process is a heat-transfer rate control stage, thus the drying rate depends on the heat transfer rate from heat source to the coal particles. On the other hand, non-freezable water drying is a mass-transfer rate control stage governed by the water diffusion in the particle. A higher bed temperature would generate a large driving force and remove more amount of non-freezable water to generate a lower water content of LRC.

The removal of water from LRC would not only increase the energy density and overall power plant efficiency (by 3–5%), but also reduce the greenhouse gas emission [2]. Fluidized bed dryers are wildly used for industrial LRC drying because of their compact structure, good mixing performance, and high heat and mass transfer rates. The main challenge of LRC drying is the energy intensiveness of the process, which is due to the high latent heat of water. Although a conventional heat recovery dryer (CHR) enables utilization of the heat of the exhausted stream, it still consumes significant energy because of the inability to recover the large amount of the latent heat of water. Compression of the exhausted stream produced by evaporating water from the LRC increases the exergy rate and recovers the contained heat energy. Until now, this methodology has been applied to drying systems using both non-condensable and condensable drying mediums.

For the drying systems using non-condensable drying medium, Aziz et al. firstly developed an exergy recuperative LRC drying process with air as the drying medium showing a good energy-saving potential [3]. Unfortunately, heat transfer rate was low due to the presence of air in the steam in immersed tubes and led to a larger dryer size. Later, they solved this problem by adding an air-steam separator with a slight increase of energy consumption [4]. Liu et al. conducted exergy analysis on the drying systems and found a large exergy loss occurred due to the existence of air. A more energy-saving potential was predicted with condensable gas as the drying medium [5].

Fig. 1 shows a commercial LRC drying system, namely, a vapor recompression dryer (VRC) that uses steam as the drying medium. The VRC is capable of recycling almost the entire latent heat of the drying process by compressing the purged steam to elevate its exergy rate. Furthermore, an exergy recuperative drying system was developed with a 25% energy-consumption saving compared to VRC for a water content of 12 wt% (wb) [6]. However, the above systems consume a large amount of electricity to power the compressor that generates a medium-pressure steam. The compressed steam exchanges heat with

---

* Corresponding author.
E-mail address: yuping_liu@ihi.co.jp (Y. Liu).

http://dx.doi.org/10.1016/j.fuproc.2016.06.008

Please cite this article as: Y. Liu, H. Ohara, Energy-efficient fluidized bed drying of low-rank coal, Fuel Processing Technology (2016), http://dx.doi.org/10.1016/j.fuproc.2016.06.008

Nomenclature

A	heat exchange surface area, m^2
Ar	Archimedes number, dimensionless
a	heat transfer coefficient, W m^{-2} K^{-1}
C_p	heat capacity at constant pressure, kJ kg^{-1} K^{-1}
C_d	orifice discharge coefficient, dimensionless
c	conversion factor, 1 kg m N^{-1} s^{-2}
c_v	local solid fraction, dimensionless
d	diameter, m
g	gravity acceleration, m s^{-2}
H	thermal energy, kW
ΔH_{vap}	water evaporation enthalpy, kJ kg^{-1}
h	bed height, m
h_c	overall heat transfer coefficient, W m^{-2} K^{-1}
L	length of tube, m
M	water content, wt% wb
m	mass flow, kg h^{-1}
n	polytropic exponent, dimensionless
N_{cap}	number of bubble caps, dimensionless
N_o	orifice number of each cap, dimensionless
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
p	absolute pressure, kPa
R	outer diameter, m
Re	Reynolds number, dimensionless
r	inner diameter, m
T	temperature, K
ΔT_{min}	minimum temperature difference in heat exchanger, K
U	fluidization velocity, m s^{-1}
U_b	local bubble rise velocity, m s^{-1}
U_{mf}	minimum fluidization velocity, m s^{-1}
W	work, kW
x	steam ratio, dimensionless
Greek letters	
η_{el}	power generation efficiency, dimensionless
ρ	density, kg m^{-3}
ε	voidage, dimensionless
λ	thermal conductivity, W m^{-1} K^{-1}
ν_b	visible bubble flow rate, m s^{-1}
ν_g	kinematic viscosity of gas, Pa s
ν_s	specific volume, m^3 kg^{-1}
υ	volumetric fraction, dimensionless
θ	hydrodynamic parameter, dimensionless
Subscripts	
0	standard condition
b	bubble
bl	blower
c	condense
cp	compression
crit	critical
d	distributor
g	gas
i	state
in	incoming flow
l	liquid
o	orifice
out	outgoing flow
s	solid particle
sf	superficial
st	steam turbine
t	tube
tot	total

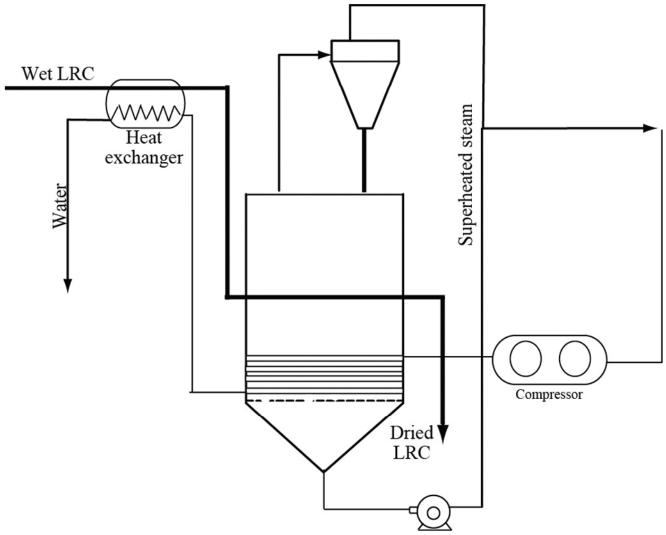

Fig. 1. Schematic process of vapor recompression dryer.

LRC which needs to be heated to above 110 °C for a water content of less than 12 wt% (wb) [7]. Liu et al. minimized the energy consumption by separately removing the freezable and non-freezable water from the LRC using self-heat recuperation technology. Electricity consumption was reduced by over 40% compared to VRC, however, two compressors were required and the consequent high capital cost limited its utilization [8]. Thus, a trade-off exists between the energy-saving performance and capital cost.

In the present study, a fluidized bed drying process was developed for energy-saving and economical drying of LRC. The proposed process utilizes an exergy recuperative module for the removal of freezable water based on the self-heat recuperation technology, a heat integration module for the removal of non-freezable water, and a cooling module for the cooling of the hot LRC particles. To reduce the capital cost, a blower was used instead of an expensive compressor for the removal of freezable water. We also reduced capital cost in the non-freezable water dryer by exploiting the heat of the medium-pressure steam extracted from the steam turbine. Since non-freezable water removal took part of less than 15% of total energy supply, application of self-heat recuperation technology would slightly reduce the energy consumption, however, dramatically increase capital cost. Energy consumption of the proposed process was investigated and compared with those of existing energy-saving drying processes. Moreover, several types of self-heat recuperative drying processes have been proposed with more heat exchange tubes required in the fluidized bed than conventional fluidized bed dryer. We thus studied the effect of increased heat exchange tubes on the fluidization behavior of LRC particles to confirm the technical feasibility of self-heat recuperation technology application for the fluidized bed drying process based on simulation study.

2. Process simulation

2.1. Schematic of the proposed drying process

A schematic illustration of the proposed drying process is shown in Fig. 2. The raw LRC with its high water content is inputted to a coal miller to reduce the mean diameter of the coal particles to a small value. The LRC is then preheated for heat exchange with condensed hot water, after which the LRC particles are introduced into the fluidized bed dryer to remove the contained water. The evaporation of the water occurs in two separate modules, namely, an exergy recuperative module in which the freezable water is removed, and a heat integration module where the non-freezable water is removed. In the former module, the freezable water in the LRC is evaporated by the heat supplied from

Please cite this article as: Y. Liu, H. Ohara, Energy-efficient fluidized bed drying of low-rank coal, Fuel Processing Technology (2016), http://dx.doi.org/10.1016/j.fuproc.2016.06.008