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Online identification of the lower heating value of the coal entering the furnace based on the boiler-side whole process models

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HIGHLIGHTS

- A model-based online approach of identifying the LHV of the coal is proposed.
- The boiler-side whole process is modeled based on the thermodynamic balances.
- The mass flow rate of the coal and the total output energy are accurately calculated.
- A transfer function model is applied to approximate the phase mismatch.
- The accuracy of the approach is well validated with offline assays of the LHV.

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ABSTRACT

The lower heating value (LHV, also called net calorific value, NCV) of the coal entering the furnace is one of the most important variables for process optimization. However, in most cases, it is not online measurable in coal-fired power plants. In this paper, an online identification approach of the LHV is proposed based on the boiler-side whole process models together with the real-time data acquired by the distributed control system (DCS). The boiler-side whole process models cover typical facilities of a power plant, and are established based on dynamic mass and energy balances. The accurate estimation of the mass flow rate of the coal entering the furnace and the total output energy of the boiler is the highlight of the approach. Rolling identification of the LHV of the coal is presented to take the intrinsic time variant characteristics of the coal combustion and heat transfer processes into account. To validate the proposed approach, pseudo-online simulations are carried out with the history data of a real 300 MW coal-fired power plant. The mean absolute relative error between the calculated LHVs and their original assays is found less than 5.0%, and the mean absolute relative error becomes less than 1.1%, if the rectified assays are used.

1. Introduction

Coal-fired electricity generation is the dominant source of power supply worldwide nowadays as well as in the foreseeable future [1]. For decades, thermal and control engineers have made numerous efforts to save the energy and reduce the emission of pollutant and greenhouse gases for the coal-fired power plants [2–7]. These efforts do result in significant reduction of the net standard coal consumption rate. Taking China as an example, the net standard coal consumption rate has dropped to 318 g/kW h in 2014 from 340 g/kW h in 2009 [8]. As a very common and vital indicator of coal quality [9], heating value is essential in the coal blending and the economy assessment of the coal-fired power plants, and plays a very important role in the combustion control system for the automatic generation control (AGC) [10].

In the combustion control system, the demand for the total fuel quantity is generally calculated based on the design coal. However, in engineering practice, the kinds of coal are so diverse both in their origins and ages [11] that the actual heating values of the feed coal are often different from that of the design coal. Therefore, the heating value correction is of necessity for ensuring the feed coal to meet the load demand. One common control strategy is that the mass flow rate of the main steam is adopted to indicate the actual heat load [12] and the heating value compensation coefficient is determined according to the deviation between the actual heat load and the load demand. Another strategy is to use the direct energy balance (DEB) control [13,14], so as to balance the heat

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Nomenclature

Δt	sampling period (s)
h	specific enthalpy (kJ/kg)
l	length (m)
m	mass (kg)
p	pressure (MPa)
s	laplace operator (dimensionless)
u	control variable (V)
v	specific volume (m^3/kg)
A	cross-sectional area (m^2)
D	mass flow rate of working fluid (kg/s)
F	mass flow rate of flue gas (kg/s)
L	mill level (m)
M	time window (dimensionless)
N	time window (dimensionless)
P	unit load (MW)
Q	energy (MW)
$Q_{gr,ar}$	higher heating value (MJ/kg)
$Q_{net,ar}$	lower heating value (MJ/kg)
T	temperature (K)
V	volume (m^3)
W	vector length (dimensionless)

Greek letters

τ	delay time (s)
λ	length (m)

Subscripts

ac	actual value
ar	as-received basis
as	assay value
c	compensation
cf	coal entering the furnace
cb	continuous blowdown
d	dry
eg	exhaust flue gas
fc	feed coal
fw	feed water
m	metal
ms	main steam
npc	newly pulverized coal
or	original
p	pulverizing process
pa	primary air
re	rectified
ref	reference
s	saturation steam
sd	steam leaving from the drum
tp	two phase
t,in	total input
t,out	total output
w	saturation water
CAR	coal–air ratio
WW	water wall
SH	superheater
RH	reheater
EC	economizer
HEX	heat exchanger

Superscripts

$'$	inlet
$''$	outlet

demand of the turbine and the heat supply of the feed coal with varying coal quality. However, these control strategies cannot correct the variant of coal quality timely.

The bomb calorimeter method is relatively simple and reliable to determine the higher heating value (HHV, also called gross calorific value, GCV) of the coal sample [15]. The HHV and the lower heating values (LHV, also called net calorific value, NCV) are interconvertible each other [16,17]. However, the experiment process costs a long time and needs the excellent skills of chemists. Hence, for decades, many simplified formulas based on the composition of the coal have been presented in the literature. They are basically classified into two categories: (a) correlations based on the proximate analysis [18–20]; (b) correlations based on the ultimate analysis [21,22]. These formulas are still dependence of offline experiment analysis and only applicable for specific few kinds of coal.

Up to now, there have been some online coal quality measurement instruments, which adopt three major techniques [23,24]: dual energy gamma-ray transmission (DUET), prompt gamma neutron activation analysis (PGNAA), and neutron-induced gamma analytical techniques. Nevertheless, they are rarely used in most power plants due to the high price and maintenance cost.

In the literature, data-driven methods also have been published to predict the heating value of coal using artificial nervous network [25–27], fuzzy inference system [28], multiple regression method [29], etc. Some of them need input the composition of the coal through the proximate or ultimate analysis into the models [25,28]; the others take several highly relevant process variables as input, such as mass flow rates of the main steam and the reheat steam, coal feeder speed, total air amount, etc. [26,27]. Apparently, the latter have better generalization capability for the various kinds of the coal and are more suitable for online application than the former. More recently, coal quality is correlated with the multi-spectral flame radiation features extracted from the photoelectric sensors [29]. However, all of these data-driven methods need numerous reliable input and output data in advance and have to be retrained when the performance of the unit or the photoelectric sensors shifts.

The online identification of the LHV based on the enthalpy balance is a very promising method [30]. The key is the explicit consideration of all aspects having impact on the enthalpy balance and detailed dynamic models. Oversimplification on the heat loss calculation and ignorance of the intrinsic distributed and dynamic characteristics of the whole process [30] will significantly reduce the accuracy of the dynamic enthalpy balance.

In this context, this study develops a new online identification approach of the LHV of the coal entering the furnace based on the boiler-side whole process dynamic models. It makes full use of the real-time operation data acquired by the distributed control system (DCS), and is not restricted by the coal kind.

2. Overview of the proposed approach for online identifying the LHV

Fig. 1 illustrates the framework of the proposed approach for online identifying the LHV of the coal entering the furnace. The boiler-side whole process models consist of five sub-modules, i.e. pulverizing system, evaporation system, heat exchangers (including superheaters, reheaters, and economizer), heat losses and metal wall energy compensation models.