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Fuel-quality soft sensor using the dynamic superheater model for control strategy improvement of the BioPower 5 CHP plant

J. Kortela [*], S.-L. Jämsä-Jounela

Aalto University, P.O. Box 16100, FI-00076 Aalto, Finland

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ABSTRACT

This paper presents an enhanced method for estimating fuel quality in a BioGrate combustion process and the method's use in control strategy improvement. This method is based on a dynamic model that makes use of combustion power estimates – which can be calculated based on the furnaces oxygen consumption – and that makes use of a nonlinear dynamic model of the secondary superheater. The paper focuses to estimate the most essential combustion parameters: fuel moisture and fuel flow. The time delay for detecting a change in fuel moisture and fuel flow is small enough for the method to be used for controlling both air and fuel feed, preventing any steam and pressure oscillations. The proposed control strategy is compared with the method currently used in the BioPower 5 CHP plant. Finally, the results are analyzed and discussed.

1. Introduction

Increased utilization of renewable energy has created new energy efficiency challenges in industry, where biomass is one of the most important raw materials for renewable energy. Grate firing is one of the main technologies that are currently used in biomass combustion for heat and power production [10,15]. Though the grate firing of biomass has been tried and tested over many years, there are still some problems requiring further study, for instance, the conversion of biomass in the fuel bed, the mixing of burning substances in the fuel bed and on the freeboard, deposit formation and corrosion and their control, and pollutant formation and control [18]. One of the newest successful processes which use wood waste as fuel is a BioGrate boiler technology developed by MW Power. In this process, grate boilers are used as steam generation units to control a steam network. Rapid steam load changes necessitate good stability and load following properties in the system. Therefore, both drying and combustion in the grate must be controlled properly [8]. The main disturbances to the boiler are caused by fuel quality variations. The chemical properties of even the same type of biofuel may differ greatly, for example due to harvesting, storing, and transport conditions [18]. The ability to compensate variations in fuel quality thus plays a key role in controlling the combustion process.

An essential early step in developing a control strategy has been to develop a method for estimating a furnace's fuel flow and combustion power. As shown in the theoretical studies and practical tests by Kortela and Lautala [7] for a coal power plant, a furnace's fuel combustion power can be estimated on the basis of the measured oxygen consumption. On-line measurement of oxygen consumption was used when a new cascade compensation loop was built to optimally control the fuel flow. In that control strategy, the set point of the fuel feed mainly depends on the output of the drum pressure control. The amount of fuel burned is estimated using the flue gas oxygen content, and the fuel feed set point is modified accordingly. The control uses an integrator to remove steady-state offset in the control loop. It was reported that the amplitude and the settling time of the response of the generator power decreased to about one third of the original when this cascade compensation loop was added to the present system.

Combustion power control (CPC) was implemented also in peat power plants [11], where it was able to stabilize the furnaces. The control actions of the burning air flow decreased when variations in the oxygen consumption were eliminated. The control strategy could thus reduce the standard deviation of the flue gas oxygen content, and the air flow could be lowered close to the optimal flow. As a consequence, the flue gas losses were reduced. Furthermore, the stabilized steam temperatures reduced thermal stress on superheaters and connected pipes. In addition the same approach has been applied to minimize (NO_x), (SO_2) and (CO) emissions in a bubbling fluidized bed boiler in [9,12], where the use of the combustion power control algorithm made it possible to stabilize the

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* Corresponding author. Tel.: +358 9 470 22647; fax: +358 9 470 23854.
E-mail addresses: jukka.kortela@aalto.fi (J. Kortela), sirkka-l@hut.fi (S.-L. Jämsä-Jounela).

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Nomenclature

α	correction coefficient
μ	viscosity, N s/m^2
ρ	density, kg/m^3
ϱ	specific density, kg/m^3
A	area, m^2
c	specific heat capacity, MJ/kg K
C_1	constant of a tube bank of 10 or more rows
C_i	specific heat capacity, J/molT
F	volume flow, m^3/s
g	gravitational acceleration, m/s^2
h_f	specific enthalpy of the feed water, MJ/kg
h_i	heat transfer coefficient, W/m^2 K
h_s	specific enthalpy of the steam, MJ/kg
k	radiation heat transfer coefficient
k_f	thermal conductivity, W/m K
L	characteristic length of the surface of interest
m	mass flow, kg/s
M_i	molar mass, g/mol
m_t	total mass of the metal tubes and the drum, kg
m_{Air}	theoretical amount of air needed to combust one kilogram of fuel, kg/kg
m_{fg}	flue gas flow for one kilogram of fuel kg/kg
m_{gf}	fuel flow, kg/kg
N	prediction horizon
N	moles needed to burn completely one kilogram of a fuel, mol/kg
n_i	moles, mol/kg
Nu	Nusselt number
P	net combustion power, MW
p	pressure, N/m^2
Pr	Prandtl number
Q	heat transfer from the flue gas to the steam/water, MJ/s
q	heat value, J/kg
Q_m	heat transfer from the flue gas to the metal walls, MJ/s
q''_s	heat transfer
Q_t	heat transfer from the metal walls to the steam/water, MJ/s
Re	Reynold's number
T	temperature, °C
T_∞	free stream temperature, K
T_s	surface temperature, K
u	velocity component along the surface
u_i	specific internal energy, MJ/kg
V	velocity upstream of the surface
V	volume, m^3
v	velocity component normal to the surface
w	fuel moisture content, %
w_i	mass fraction, %
X	volume, %
x	direction along the surface
y	direction normal to the surface
σ	surface tension, N/m
$C_{s,f}$	constant of solid–liquid combination
T_e	excess temperature, K
v	water

Subscripts

$*$	dimensionless parameter
0	reference value
Air	air
b	boiling
C	carbon
c	convection
cr	convection and radiation
D	circular tube
D, *max*	maximum fluid velocity
ds	de-superheating spray
f	feed water
fg	flue gas
gf	wet fuel
H	hydrogen
in	input
l	liquid
m	metal
N	nitrogen
O	oxygen
out	output
p	metal
p, *air*	air
p, *fg*	flue gas
S	sulphur
s	steam
v	vapor
w	water
wf	dry fuel

Superscripts

m	constant of a tube bank of 10 or more rows
n	constant of solid–liquid combination

burning conditions in co-combustion. This led to better control of flue gas emissions, and it was reported that the combustion power control reduced steam pressure deviation by 50%.

Model-based predictive control has been used by Havlena and Findejs [3] to enable tight dynamical coordination between air and fuel intake to take into account variations in power levels. The results showed that this approach can be used to increase boiler efficiency while considerably reducing NO_x emissions. Similar results have also been reported for the application of a multivariable long-range predictive control (LRPC) strategy based on a local model network (LMN) in the simulation of a 200 MW oil-fired drum-boiler thermal plant [16].

However, there are still some challenges and unattained objectives in the development combustion power control. For example, variations in the moisture of fuel should be taken into account in order to correct any estimation errors of combustion power. The varying moisture content of the fuel results in uncertainty in the energy content of the fuel and complicates operation of the combustors. The typical procedure to determine moisture content of the fuel in small or medium-scale grate furnaces is to analyze manually collected samples of each fuel batch delivered to the plant. This method, however, is not accurate enough to predict moisture content of the fuel mix that enters the furnace. A change in moisture content of the fuel has to be detected at a resolution of seconds that the control system is able to make a correct response to the combustion combustion air and the fuel feed system. There is, thus, a special need for a control system or for an operator to have information about moisture content for necessary adjustments of the combustors to be made.

A typical method for determining fuel moisture content is to determine first moisture content of the flue gas from which the moisture content can be then derived by a mass balance calculation [8]. The only delay of the measurement signal in this setup is the transport time of the gas from the furnace to the