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An innovative bed temperature-oriented modeling and robust control of a circulating fluidized bed combustor

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Abstract

Circulating fluidized bed (CFB) combustion systems are increasingly used as superior coal burning systems in power generation due to their higher efficiency and lower emissions. However, because of their non-linearity and complex behavior, it is difficult to build a comprehensive model that incorporates all the system dynamics. In this paper, a mathematical model of the circulating fluidized bed combustion system based on mass and energy conservation equations was successfully extracted. Using these correlations, a state space dynamical model oriented to bed temperature has been obtained based on subspace method. Bed temperature, which influences boiler overall efficiency and the rate of pollutants emission, is one of the most significant parameters in the operation of these types of systems. Having dynamic and parametric uncertainties in the model, a robust control algorithm based on linear matrix inequalities (LMI) have been applied to control the bed temperature by input parameters, i.e. coal feed rate and fluidization velocity. The controller proposed properly sets the temperature to our desired range with a minimum tracking error and minimizes the sensitivity of the closed-loop system to disturbances caused by uncertainties such as change in feeding coal, while the settling time of the system is significantly decreased.

Keywords: Circulating fluidized bed (CFB); Bed temperature; Subspace identification; Robust control; Linear matrix inequalities (LMI)

1. Introduction

Today there is no doubt that fluidized bed combustion (FBC) systems are superior to all other combustion technologies in burning low quality coals, biomass and other waste fuels. Effective combustion with high system efficiency even for low-reactivity fuels is accessible with applying a proper control structure, and it is possible for these kinds of systems to achieve combustion efficiency of up to 99.5% [1]. On the other hand, combustion of coal with high sulfur content, when strict requirements for environmental protection have to be satisfied, is feasible only in FBC systems. These systems are noticeably suitable for steam generation purposes in high capacities in power plants as they can satisfactorily respond to variations in load demands. They can handle load changes of up to 4% per minute without any problems [2].

“Fluidization” refers to the condition in which solid materials are given free-flowing, fluid-like behavior. As gas is passed upward through a bed of solid particles, the flow of gas produces forces which tend to separate the particles from one another [3]. In a typical FBC which uses air as the fluid (atmospheric fluidized bed), fine particles of coal are injected to the bed by air. Air nozzles are located in the bottom and the combustion chamber wall. Injected coal particles first produce volatiles over a relatively short period of time. The char particles which remain after complete devolatilization burn for a relatively long period of time [4]. With an increase in air velocity, large amounts of particles are carried out of the bed with the air. Entrained particles must be collected by the cyclone (which includes standpipe section) and returned to the bed. These types of systems are generally called circulating fluidized beds (CFBs). CFBs use a higher fluidizing velocity, so the particles are constantly held in the flue gases, and pass through the main combustion chamber and into the cyclone. Fig. 1 shows a simplified diagram of a circulating fluidized bed combustor.

The fluidized bed is not yet a fully understood system and its dynamics is very complex because of its chaotic nature, non-

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Nomenclature

A	surface area (m^2)
A'	constant in Eq. (14)
c	specific heat capacity (kJ/kg K)
C_g	oxygen concentration in the free stream (kPa)
d	diameter (m)
D_b	bed diameter (m)
D_g	molecular diffusivity of oxygen (m^2/s)
E	activation energy (kJ/kmol)
G	average circulation rate (kg/m^2 s)
h	total heat transfer coefficient (W/m^2 K)
h_m	mass transfer coefficient (kg/m^2 kPa s)
H	bed height (m)
H_c	combustion heat (kJ/kg)
H_v	heat produced by combustion of volatiles (kJ/kg)
k_a	attrition constant
k_c	char reaction rate coefficient (kg/m^2 kPa s)
k_g	thermal conductivity of the gas (W/m K)
m	mass (kg)
M	bed mass (kg)
P	bed pressure (kPa)
P	heat generated per unit time (kJ/s)
P_a	power delivered to heat the air mass flow from the inlet temperature to the bed temperature (kJ/s)
P_b	heat generated per unit time by the burning of char (kJ/s)
P_{bw}	heat transported from the bed to wall heat exchangers (kJ/K)
q	volume flow rate (m^3/s)
Q	heat per unit time (kJ/s)
R	universal gas constant (kPa m^3/kmol K)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
T_m	mean temperature of the diffusion layer around the carbon particle (K)
u_s	slip velocity (m/s)
U	fluidization velocity (m/s)
V	volume (m^3)
x_v	fraction of volatile matters

Greek letters

ε	bed voidage
ζ	particle porosity
μ	viscosity of gas (kg/m s)
ρ	density (kg/m^3)
ρ_s	suspension density of the bed (kg/m^3)
φ	combustion reaction mechanism factor
ω_a	attrition rate (kg/s)
ω_b	char burning rate (kg/s)
ω_c	char flow rate (kg/s)
ω_f	burning rate of fine particles (kg/s)
ω_i	coal feed rate (kg/s)

Subscripts

b	bed
c	char
c	convective
f	fines
g	gas
m	number of inlet flows
mf	minimum fluidization
p	particle
r	number of outlet flows
s	number of heat sources and consumptions
s	solids
v	volatiles
w	wall heat exchangers

linearity, and number of immeasurable unknown parameters [5]. Obviously, the conditions under which the combustion of coal particles in a fluidized bed takes place are significantly different from the combustion conditions in other types of boilers. Research on these combustion processes requires an understanding of coal combustion process in fluidized beds.

The dynamics of multi-phase flow and process characteristics of circulating fluidized bed boilers have been discussed by many authors [5–12]. The goal of these research projects has been the mathematical modeling of gas/solid flow in different parts of the fluidized bed; however, they are mainly focused on cold systems and the particles flow dynamics. Hence, bed temperature and its effects on system dynamics are ignored. Modeling and control of combustion process when the system works in real conditions have been studied by [13–18]. Bed temperature, which influences steam temperature and boiler overall efficiency, is one of the most significant parameters in the operation of these types of systems. Many other reasons for controlling bed temperature

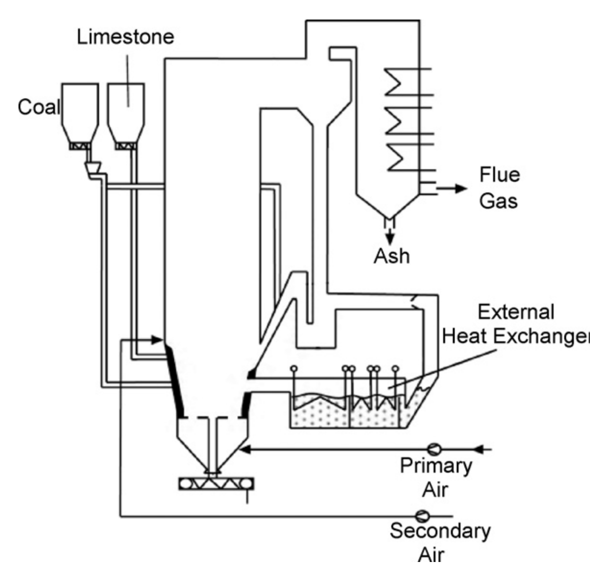

Fig. 1. Schematic diagram of a circulating fluidized bed combustion system.