Available online at www.sciencedirect.com
ScienceDirect
Powder Technology 169 (2006) 123–135
POWDER TECHNOLOGY
www.elsevier.com/locate/powtec

Short Communication

Inverse measurement method for detecting bubbles in a fluidized bed reactor—toward the development of an intelligent temperature sensor

J. Oliveira, J.N. Santos, P. Seleghim Jr. *

Thermal and Fluid Engineering Laboratory, School of Engineering of São Carlos, University of São Paulo, Av. Trabalhador Sancarlense, 400, 13566-590, São Carlos-SP, Brazil

Received 9 August 2005; received in revised form 25 May 2006; accepted 31 July 2006
Available online 11 August 2006

Abstract

The objective of this work is to contribute to the development of an intelligent temperature sensor capable of reconstructing the actual process temperature from the indicated temperature signal through numerical solution of the inverse transduction problem. In addition, it is required that the reconstruction algorithm results in a small computational code, suitable for implementation in a commercial microcontroller for on-line monitoring. The necessary regularization technique was based on extracting derivatives and current indicated values from a low order polynomial fitted to the last few temperature readings. Numerical and experimental results show that the proposed technique allows the reconstruction of the process temperature under realistic experimental conditions at relatively high noise levels.

Keywords: Temperature sensor; Inverse model; Regularization; On-line measurement

1. Introduction

Gas bubbling fluidized beds are used in the industry for a variety of purposes, such as the catalytic cracking of hydrocarbons and the combustion of coals. A gas bubbling fluidized bed may be regarded as a mixture comprised of two phases, a bubble phase and a particulate or emulsion phase. Bubbles are dispersed within the continuous emulsion phase and are formed as the fluidizing gas is injected at the bottom of the bed. They move upwards dragging wakes of particulate and may coalesce into larger bubbles, split and recoalesce. These intricate and interdependent phenomena result in an extremely complex gas–solid flow dynamics, characterized by high reaction and heat transfer rates. A complete understanding of such phenomena is of crucial importance, not only for the correct design of fluidized bed reactors, but also for their efficient and safe operation.

The properties and evolution of bubbles in gas fluidized beds are investigated using either intrusive or non-intrusive measuring techniques. Measurements through capacitive and electroresistive external probes, optical and X ray observations through photography and filming, with or without the use of gas tracers, are among the most common non-intrusive methods. These methods, even though not disturbing the process, are either limited to small beds or allow observations only near to the confining walls. Intrusive techniques are based on phase detection probes for measuring local physical properties. The majority of commonly used probes are thermal, capacitive, optical, differential pressure, and electroresistive. Regardless of disturbing the process to some extent, intrusive probes are applicable to reactors of any size and certainly constitute the most adequate choice in large-scale industrials systems.

The main problem involved in probing gas–solid flows in fluidized bed reactors concerns the extremely harsh environment in which the sensor is immersed: temperatures exceeding 800 °C, material deterioration due to friction with the fluidized particulate, chemical corrosion, presence of electrostatic charges, etc. Thermal probes are an interesting option to work in such conditions because of low cost and intrinsic robustness. Detecting gas bubbles with a thermal probe is based on the temperature difference between the hotter reacting emulsion phase and the colder gas bubbles phase. Consequently, the signals delivered by

* Corresponding author. Tel.: +55 16 33 73 94 16; fax: +55 16 33 73 94 02.
E-mail address: seleghim@sc.usp.br (P. Seleghim).

0032-5910/$ - see front matter
doi:10.1016/j.powtec.2006.07.021

Nomenclature

a_i	polynomial coefficients
A	area (m^2)
A_i	coefficient of the first line in G^{-1}
B_i	coefficient of the second line in G^{-1}
C	specific heat (kJ/kg/K)
ε	emissivity
G	Gram's matrix
h	convection coefficient ($W/m^2/K$)
m	mass (kg)
σ	Stefan–Boltzmann constant ($=5.670\times10^{-8}$ $W/m^2/K^4$)
t	time (s)
T_{ind}	indicated temperature (K)
T_{proc}	indicated temperature vector (K)
T_∞	temperature at which radiative heat transfer occurs (K)
w_{k}	weight coefficient
x	polynomial support axis (s)
Δt	time step (s)
τ	time constant (s)
M	number of points
N	polynomial order
$e(\,)$	error function (k^2)
γ	radiation coefficient
$T_{\mathrm{smooth}}(\,)$	temperature polynomial (K)
k	summation index
τ_0	time constant at 317.5 K (s)
λ	thermal drift (s/k)
n	time index

such thermal probes tend to concentrate around characteristic levels and can be used to construct the so-called phase indicator signals, which by definition assumes binary values depending on which phase is instantaneously in contact with the sensor. The processing algorithm capable of transforming noisy measurements into the corresponding phase indicator signals has been studied by Zun et al. [1], who proposed a discrimination technique based on threshold levels previously optimized from a genetic algorithm, and by Seleghim and Milioli [2] which used wavelet filtering in association with Ville's instantaneous frequency to extract the edges of the measured signal. Although their important contribution, the problem remains an interesting research challenge, especially if on-line processing is envisaged and because the reconstruction procedure is strongly dependent on the physics of the interaction of the flow and the probe.

From an industrial application perspective, the importance of constructing the phase indicator signal is due to its application in monitoring the fluidization process to obtain better overall efficiencies. In particular, the phase indicator signal is the primary input in the determination of important physical description parameters such as residence times, bubble diameter histograms, etc., which are crucial for an optimized operation of the fluidization process. In a fluidized bed reactor, the efficient and clean production of energy from coal combustion depends on maximizing reaction rates and on controlling the bulk temperature around a previously determined value to minimize the production of sulphur and nitrogen oxides, for instance. To accomplish this, it is necessary to control the total interfacial area between the coal emulsion and gas bubbles, which implies the control of the flow regime in a way that only small bubbles are generated (the gas contained in large bubbles tends to lower the temperature and to by-pass the bed without reacting [3]).

There is, however, significant limitations involving the possibility of obtaining some of these physical description parameters. For instance, previous works account for the problem of determining a bubble diameters histogram from the corresponding measured pierced lengths histogram, which implies solving an extremely ill-conditioned integral equation. The consequence of this is that negligible experimental errors may be amplified to the point of completely corrupting the reconstructed histogram. Also, any distortion of the measured signals, even at favorable signal-to-noise ratios (SNR), may seriously compromise the significance of the results. Since experimental errors and measurement distortions are unavoidable, special signal processing techniques must be applied to manage such problems in order to obtain acceptable results [2].

This work is focused on the problem of developing a numerical signal processing technique capable of reconstructing the original process temperature signal from its distorted, delayed and shifted measured signal delivered by an intrusive probe. In