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Development of a non-invasive optical technique to study liquid evaporation in gas–solid fluidized beds

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HIGHLIGHTS

- Development and demonstration of a non-invasive experimental technique.
- Simultaneous, whole field determination of solids flux, holdup and temperature.
- Post-processing of infrared images employs simultaneously taken visible light images.
- Evaporation of liquid in a pseudo 2D gas fluidized bed at elevated temperature.
- Observation of temperature effects in the solid phase, due to liquid evaporation.

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ABSTRACT

A non-invasive experimental technique based on particle image velocimetry and digital image analysis on images acquired with high-speed cameras operating in the visual and infrared wavelengths has been developed. With this, simultaneously whole-field data on the evolution of flow patterns and particle temperature distributions in a gas-fluidized bed with and without liquid injection can be obtained. A dedicated pseudo-2D gas–solid-fluidized bed was constructed and operated with liquid injection via a nozzle spraying onto the fluidized bed.

It was found that for proper processing of the data recorded with the high-speed infrared camera, combination with digital image analysis on images acquired from the visual camera is essential. The application of infrared thermography to gas fluidized beds suffers from the effects of interparticle reflections. The paper addresses the calibration procedure in detail and it is shown how to correct for this. The temperature-dependent effect of the setup window in the calibration is evaluated. To demonstrate the potential of the technique, it has been applied to dry fluidization and fluidization with liquid injection.

1. Introduction

Gas–solid fluidized beds are known for the favorable property of operation at relatively uniform temperature, even when significant sources and sinks of heat are present. Liquid injection in gas fluidized beds has been employed industrially for decades, for example in evaporative cooling of polyolefin reactors (Jenkins et al., 1986) and in catalytic cracking (House et al., 2008). For a long time, the mechanism of distribution and subsequent evaporation of liquid after injection into a gas fluidized bed remained difficult to ascertain (Bruhns and Werther, 2005) and this made it difficult to, for example, increase the amount of liquid injected (to evaporate) per bed volume. In part, this is due to difficulties in the interpretation of results from (single point) invasive probes (Table 1), for example for thermocouples (Bruhns, 2003; Leclère et al., 2004), which leaves questions in the field of heat transfer limitations open. Non-invasive techniques monitoring phenomena on the scale of the bed have amongst others allowed to distinguish between “free liquid” and liquid bound in liquid–solid agglomerates, and identified typical conditions for agglomerate breakage, if formed (Table 2).

Whole-field camera recordings of relevant phenomena have shown enormous value in enhancing our understanding. Modern techniques allow to observe phenomena that until recently were inaccessible, e.g. (Cocco et al., 2013). Automated quantitative analysis of images obtained allows for quantification, ensuring proper interpretation and for revealing system features that might otherwise remain unnoticed. Optical techniques can employ

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Nomenclature

Greek symbols

λ	wavelength
σ	standard deviation
τ	Eq. (11).
τ	transmissivity

Alphabetical symbols

a	coefficient
b	coefficient
b	bed
c	coefficient
d	coefficient
e	coefficient
e	emissivity
f	volume fraction
f	probability density
F	Eq. (1).
i	index
I	infrared flux
j	index
n	number of samples
r	signal distribution
s	signal (pre-corrected)
t	time
T	temperature
u	velocity
w	window
x	displacement
x	sample value
x	horizontal direction
y	vertical direction
z	raw camera signal

(high-speed) cameras that detect visual light, but also cameras that detect wavelengths in the infrared. Non-invasive determination of the temperature via infrared, in combination with visual techniques (e.g. applied by Yamada et al. (2002) to detect stagnant solids), brings opportunity for the study of liquid injection into gas-fluidized beds and associated effects such as (non)agglomeration of solids and heat transfer limitations.

Table 1
Concise overview of experimental techniques employing invasive probes to study liquid injection in dense gas-fluidized beds. This work employs a noninvasive method, instead.

Technique	Features
Temperature probes (Ariyapadi et al., 2004; Bruhns and Werther, 2005; Gehrke and Wirth, 2008; McMillan et al., 2005)	• Fast and robust • Invasive • Sticking, difficult interpretation (Bruhns and Werther, 2005) and (Gehrke and Wirth, 2008) • Mostly employed for time averages
Suction probes (Bruhns and Werther, 2005; Heinrich et al., 2003)	• Mainly for time averaged gas composition profiles • Invasive • Potential for bias by sticking liquid
Pressure probes (Bartels et al., 2010; McDougall et al., 2005a, 2005; Zhou et al., 2012)	• Common indicator of change of fluidization regime (Bartels et al., 2010; McDougall et al., 2005a, 2005) • Other techniques required to confirm interpretation (McDougall et al., 2005; Zhou et al., 2012)
Tribo-electric probes (Berruti et al., 2009; Briens et al., 2009; Portoghese et al., 2008a)	• Invasive • Sensitive to local hydrodynamics

This work presents a methodology for simultaneous application of infrared thermography, high speed visual imaging and digital post-processing, to a gas fluidized bed of particles opaque in the infrared. This was tailored to the application of liquid injection, for which a suitable experimental setup is presented. Anticipating a wide distribution of temperatures inside the gas fluidized bed, the calibration method unlike the related work of Patil et al. (2015) does account for the temperature-dependent effect of the setup window. This work has a particular attention to the width of the distribution of signals that is obtained in the infrared, and presents a method to detect the dense emulsion phase using the camera detecting visual light, to ensure proper application of the calibration. Therefore, this method, unlike that by Patil et al. (2015), also works for wide temperature distributions in the solid phase. The methodology to determine the solids flux is similar to that employed by Patil et al. (2015), opposed to the detection of single particles by Tsuji et al. (2010), which in the current application with large particle numbers is less practical. This work presents and discusses calibration results showing typical phenomena associated with the use of the technique including a demonstration for wet and dry fluidization.

2. Apparatus for measurement

The employed apparatus consists of a high-speed visual camera, a high-speed infrared camera and a pseudo-2D gas fluidized bed with a window of suitable material. The pseudo-2D geometry is required for optimal visual access. Although for this geometry the tendency of fluidized particles to stick was considered to make

Table 2
Concise overview of experimental techniques for the study of the effect of liquid injection on fluidization, requiring intermittent fluidization. In this work measurement is done during fluidization.

Electro capacitance (Mohagheghi et al., 2013; Gehrke and Wirth., 2009)	• Detection of liquid via capacitance • Signal affected by passing bubbles • Poor spatial resolution
Conductivity measurement (Leach et al., 2009; Portoghese et al., 2008b; ZirGachian et al., 2013)	• Liquid detected via conductivity • Signal disturbed by fluidization • Detection of distribution of "free liquid"
Bed excavation (House et al., 2008)	• Recovery of liquid–solid agglomerates by digging • Breakage cannot be directly observed
Artificial agglomerates with RFID trackers Parveen et al. (2013)	• Artificial agglomerates held together by permanent magnets • Breakage can be directly observed • Agglomerates re-assembled between experiments