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Applying infrared thermography and image analysis to dilute 2-phase particulate systems: Hot Particle Curtains

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Abstract

Particle curtains occur in industrial drying and in solar particle receivers and are defined as a stream of particles falling a fixed distance through a gas or fluid phase. In industrial drying optimising heat and mass transfer between the cascading particles and the drying medium is essential for enhancing energy efficiency and reducing emissions. Modelling these devices via pragmatic process systems models and/or with computational fluid dynamics models can contribute to enhanced design and a better understanding of the fundamental processes that occur. Validation of curtain modelling is critical to building confidence in the resultant predictions, but unfortunately traditional methods such as discrete temperature measurement using probes are time consuming and can disturb the flow field. Infrared thermography is an image-based technique with the potential to alleviate some of these issues and to generate whole of field temperature data, well-suited to model validation. In this paper infrared thermographic images of hot particle curtains falling through still air are presented. Image analysis methods for adjusting and scaling images as well as detecting the curtain edges are also described. Experiments involving hot particle curtains (403k-413K) falling through a narrow slot (150×20-60mm) in a room filled with still air (295K-300K) are presented. Curtain widths were varied by varying the slot width (20mm and 60mm) and a range of mass flow rates (0.04kg/s-0.155kg/s) and particle diameters (290μm and 400μm) were examined. Curtain shape, as defined by the edges of the curtains, was determined using methods adapted from image analysis. The 2D thermal images showed that the shapes of the curtains are strongly dependent on slot width or initial solids volume fraction, which has implications for maximising heat transfer in particle curtain processes.

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Keywords: Particle curtains; heat transfer; image analysis; infrared thermography.

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1. Introduction

Particle curtains are defined as a stream of particles falling a fixed distance through a gas or fluid phase. Typical unit operations that involve particle curtains are flighted rotary dryers (FRD) and solid particle receivers (SPR). In FRD's the narrow end of the curtain is exposed to cross flowing gas, while in SPR's the entire width of the curtain is exposed to solar radiation. There is a large body of literature describing models of flighted rotary dryers where estimation of curtain properties are important [1, 2] especially the effects of particle size, particle flow rate and solids volume fraction.

Typical approaches to modelling curtains are to assume curtains behave as population of particles where each particle behaves as if it is a single particle exposed to ambient gas, typically referred to as an isolated sphere approach. This approach tends to overestimate the heat and mass transfer experienced by the curtains. In addition, the drag experienced by particles within curtains is less than that for an isolated particle because particles are influenced by the bulk, which entrains gas as it falls. According to isothermal studies by Wardjiman et al. [3, 4] the shape of the particle curtains varies with initial curtain widths (i.e. initial solids volume fraction), and can lead to both divergent and convergent curtain behaviour. Kim et al. [5] and Wardjiman et al. [3, 4] studied isothermal curtain widths experimentally and observed respectively that the shape of the curtain shifted from divergent (narrows as it falls) to convergent (expands as it falls) as mass flow rate and initial solids volume fraction increased.

Relevant literature describing experimental and modelling investigations of particle curtains undergoing heat transfer with surrounding gas includes work by Hurby et al. [6], Chen et al. [7], and Wardjiman et al. [8]. Typical particle diameters and flow rates have been 200 - 650µm and 0.02 and 0.04kg/s. In all these examples model validation has involved comparison of predicted particle and gas temperatures to that obtained via direct temperature measurement using discrete sampling [6, 8]. For particle temperatures this has involved the use of small cups with holes in their bases for the particles to flow through. Cup sizes limit precision and holes must be adjusted for differing mass flowrates of particles to ensure that particles do not stagnate inside the cups. Furthermore, sampling directly within the curtains distorts the curtain flow field, making repeat experiments necessary, adding to the expense in collecting validation data. Clearly a non-invasive technique that provides particle temperature across the entire flow field would offer significant advantages over discrete measurement.

Infrared thermography is image-based non-invasive method with the potential to collect comparatively fast two-dimensional temperature profiles across the entire field of interest in particle curtain systems. Most applications of IR thermography have been in the field of reliability maintenance. The few examples of the use of applied infrared thermography to visualise temperature in the particulate systems include Yamada et al. [9], Dang et al. [10], and Patil et al. [11]. Yamada et al. [9] used IR thermography to investigate conductive heat transfer in a fluidised bed. In their research, the temperature of fluidising particles in contact with a solid heat transfer surface was visualised at the microscopic level. Infrared thermography was used to measure the temperature of single particles including glass beads with average diameters of 400µm and 600µm and iron particles, 300µm in diameter. Dang et al. [10] used infrared thermography to measure the concentration of CO_2 inside bubbles injected into a gas-particle fluidised bed. Patil et al. [11] recently combined Infrared thermography with visible image/digital image analysis to measure the temperature and infer solid volume fraction of particles in a small pseudo-2D fluidised bed (8cm wide, 20cm high and 1.5cm in depth). The fluidisation experiments were performed with glass particles of sizes 0.5mm and 1mm. The infrared camera (250×512 resolution) was placed in very close proximity to the bed surface. Individual hot particles were detectable from the background. In their research, they used threshold techniques to filter the effect of background and calculate the average temperature of individual particles. To date there are no examples of the use of IR thermography to characterise more dilute particulate systems. In this paper we present a selection of results and image analysis methods which illustrate the application of infrared thermography to obtain qualitative information characterising hot particle curtains cooling in ambient air.