

Time Resolved Photon-Counting Densitometry for Particle-Laden Liquid Flows

N. Lucido^{1,*}, P. Khokani¹, E. Andrews², H. Ganesh²

1: Dept. of Mechanical Engineering, The University of Michigan, Ann Arbor

2: Dept. of Naval Architecture and Marine Engineering, The University of Michigan, Ann Arbor

* Correspondent author: gharish@umich.edu

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ABSTRACT

In this study, time-resolved photon counting densitometry is successfully implemented to investigate two-dimensional particle-laden liquid flows. Due to the absence of background noise and readout noise, the advanced high-speed photon-counting detector demonstrated strong potential for measuring flows with density ratios on the order of unity. The resolution of volume fraction measurements depends on the selected calibration limits (ϕ_{high} and ϕ_{low}) and the source settings. Increasing the calibration range allows coverage of a broader range of volume fractions, but it also results in reduced measurement resolution. The calibration process effectively eliminates pixel-specific response variations, resulting in a uniform volume fraction field across all regions of interest. While minor discrepancies remain between expected and measured volume fraction values, the accuracy of the measurements is consistent throughout the spatial domain. The influence of X-ray source settings on the measurement quality are also presented. It is shown that postieri processing results in improved signal-to-noise making the methodology a viable candidate to investigate particle laden liquid flows.

1. Introduction

Optical opacity of many two-phase flows of interest, such as gas-liquid flows, solid-liquid flows, gas-solid flows, makes experimental investigation challenging. Among several non-intrusive non-optical measurements, X-ray radiation-based measurements of multiphase flows is viable candidate to obtain spatio-temporal density and velocity fields. X-ray-based measurements is based on Beer-Lambert's law, which relates the measured attenuation to material composition along a given ray path. In the case of nominally 2D flows, line-of-sight integrated X-ray measurements can provide insightful density field measurements. X-ray densitometry has been applied successfully to a variety of laboratory-scale systems, including liquid sprays, fluidized beds, bubble columns, ventilated cavities, and pipe flows.

Spatial, temporal, and density resolution of X-ray densitometry measurements depend on the X-ray (noise, spot-size) and the detector characteristics. X-ray detection can be broadly classified as indirect detection, where the X-ray attenuation is measured indirectly from the response of a X-ray sensitive material (scintillator screen), while direct detection involves direct measurement of X-ray photons (integrated or counts). Indirect detection results in higher noise and is not ideal for investigating multiphase flows with comparable density between the phases. Most prior studies (Gawandalkar et al., 2025; Lau et al., 2018; Mäkiharju et al., 2013) involve flows with large density contrasts between phases ($O(1000)$). In contrast, particle-laden flows like turbidity currents exhibit much smaller density ratios (0.90 - 0.99), making accurate measurements considerably more challenging. In this work, we apply X-ray densitometry using a medical X-ray source and a high-speed, photon-counting detector to measure particle volume fraction in a lock-exchange turbidity current with a density ratio of 0.93, a measurement not performed before.

Turbidity currents are gravity-driven flows characterized by a dense mixture of sediment and fluid moving into lighter ambient fluid (Gadal et al., 2023; Ikeda and Testik, 2021; Sequeiros et al., 2018). These currents occur in various natural settings such as oceans, avalanches, and volcanic flows. In this study, we systematically characterize the performance of a 2D X-ray densitometry system using a medical X-ray source and a hybrid photon-counting detector to study lock-exchange turbidity currents. Using soda-lime glass sheets, the system can be evaluated for use with glass particles of the same composition while maintaining precise, uniform calibration data.

2. Method

X-ray densitometry is used to measure volume fraction and density fields in particle-laden flows. The method is based on the Beer–Lambert law,

$$I = I_0 e^{-\mu \ell},$$

where I is the transmitted intensity, I_0 the incident intensity, μ the attenuation coefficient, and ℓ the path length.

To effectively estimate the mixture volume fraction, the attenuation produced by a known composition of uniformly distributed phase needs to be measured for each phase. I_{low} and I_{high} are then the intensity of attenuation at low volume fraction (can be zero) ϕ_{low} , and attenuation at high volume fraction ϕ_{high} . Volume fraction ϕ between these limits would be measured as

$$\phi = (\phi_{\text{high}} - \phi_{\text{low}}) \frac{\ln(I/I_{\text{low}})}{\ln(I_{\text{high}}/I_{\text{low}})} + \phi_{\text{low}}$$

Calibration is carried out using soda–lime glass sheets of the same composition as the glass bead particles. Sheets of thickness 2.38 mm are employed to span the required range of X-ray attenuation across the detector field of view. This method enables the generation of known effective volume fractions while avoiding the need to experimentally achieve the maximum packing fraction of sand particles. Prior to flow measurements, X-ray densitometry is performed on fields with prescribed volume fractions to assess the accuracy and operational limits of the measurement system. Different volume fractions within the field of view are produced by combining glass sheets with thicknesses of 0.15, 1.1, and 2.38 mm.

X-ray measurements are acquired using a DECTRIS® EIGER2 X CdTe 1M-W photon-counting detector in conjunction with a Varian G-1092 X-ray source (maximum 150 kV, 65 kW). The detector consists of one million pixels with a crystal size of $75 \times 75 \mu\text{m}$, and each pixel contains integrated electronics, enabling high-speed imaging. This configuration allows two forms of averaging: spatial averaging of photon counts across neighboring pixels to improve density resolution at the expense of spatial resolution, and temporal averaging of photon counts at individual pixels or over groups of pixels. Imaging is conducted at 500 frames per second under multiple voltage–current operating conditions. The calibrated measurements provide time-resolved, two-dimensional maps of particle volume fraction and density throughout the evolution of the turbidity current.

Turbidity experiments are conducted in a custom acrylic tank ($711 \text{ mm} \times 127 \text{ mm} \times 127 \text{ mm}$) divided into reservoir and ambient sections by a sluice gate as shown in Figure 1. The reservoir contains a sand–water mixture composed of 200 g spherical glass beads ($d_{50} = 57 \mu\text{m}$, $\rho_p = 2500 \text{ kg/m}^3$) at a concentration of 120 g/L, while the ambient section is filled with tap water. Mixing is automated for repeatability, and the gate is opened 1.2 s after mixing to limit particle settling. Due to limited size of detector ($114 \text{ mm} \times 25 \text{ mm}$), the complete evolution of the current was captured at multiple locations over the length of tank by repeating the experiment.

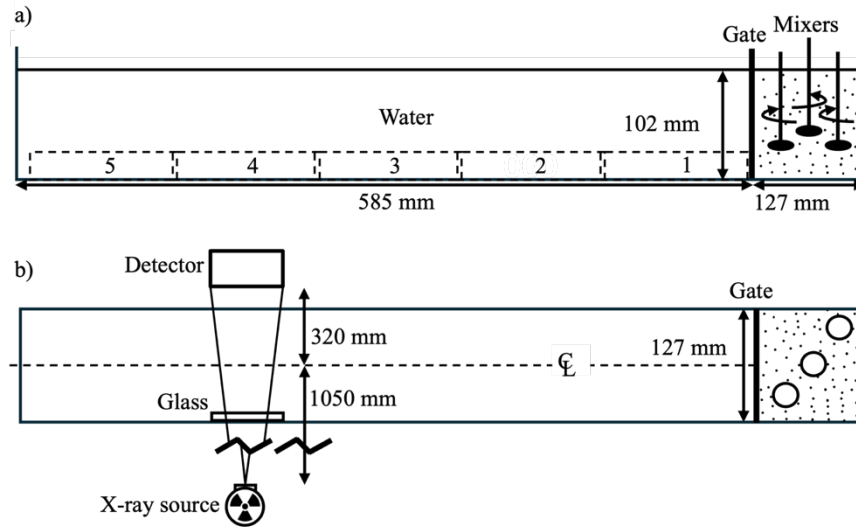


Figure 1: Schematic of X-ray densitometry setup used for calibration and measurements of an evolving lock-exchange turbidity current.

3. Results

Figure 2 presents the time-averaged photon-count image and the corresponding volume-fraction field for a representative configuration. The red boxes delineate regions with distinct volume fractions generated using different combinations of glass sheets. From left to right, the volume fractions in these regions are 0.0087, 0.0173, 0.0260, and 0.0346, respectively. Spatial variations in the baseline response of individual detector pixels introduce a visible texture in the raw photon-count image; however, this response is reproducible and is therefore accounted for during calibration. Consequently, the calibrated volume-fraction field is independent of the initial pixel response and appears spatially uniform within each region of interest.

Figure 3 compares the measured volume fractions of soda-lime sheets with known thicknesses after calibration. As shown by the unfiltered data, X-ray imaging inherently produces noisy measurements due to source characteristics, which can obscure quantitative interpretation. Applying spatial and temporal averaging substantially improves image quality and measurement accuracy by reducing noise and eliminating non-physical negative volume-fraction values. The improvement afforded by spatial averaging at the pixel level is particularly evident in the filtered data, which show markedly enhanced agreement with the known volume fractions.

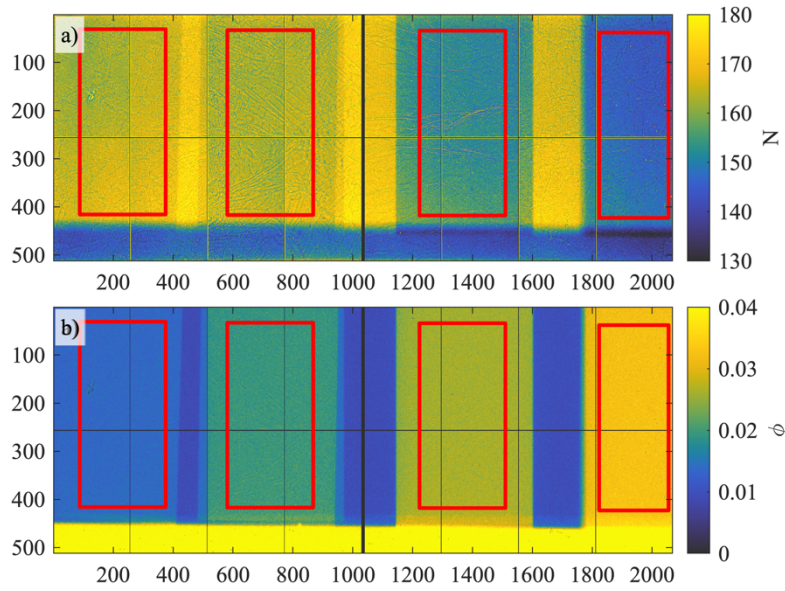


Figure 2: (a) Time-averaged photon count. (b) Volume fraction, ϕ . The red boxes indicate the regions of interest.

The presentation will outline the averaging procedure and demonstrate its application to the study of the evolution of a lock-exchange turbidity current. Figure 4 shows representative snapshots of the current for different combinations of temporal and spatial averaging. The columns correspond to increasing levels of temporal averaging, while the rows represent spatial averaging windows ranging from 1×1 to 11×11 pixels. Averaging clearly improves image quality by suppressing noise and sharpening flow boundaries. As a result, density gradients become more distinct, allowing improved resolution of the key properties of the current.

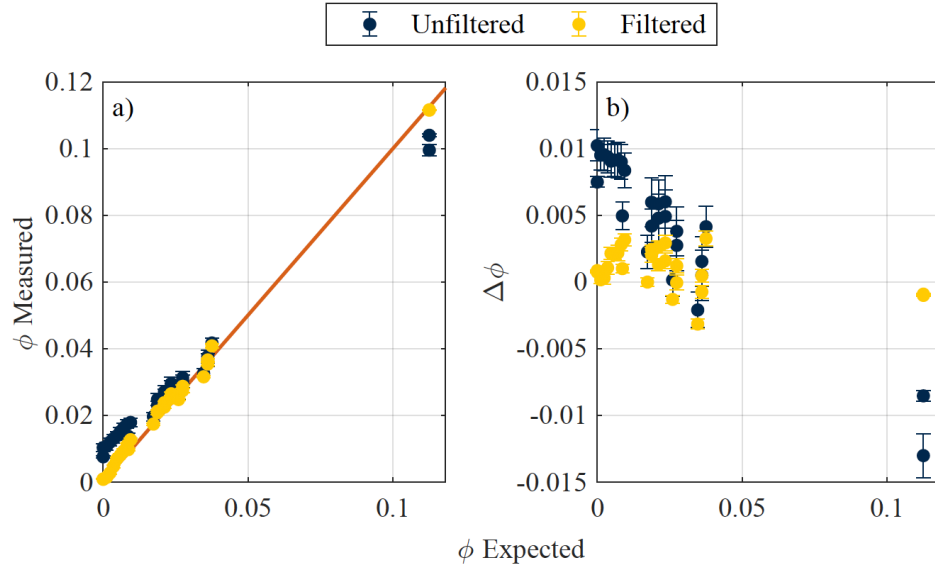


Figure 3: Comparison of measured void fraction of glass sheets with true void fraction (left) and the difference (right) for filtered and unfiltered detector settings. Spatial and temporal averaging of detector pixel values significantly improved the volume fraction resolution.

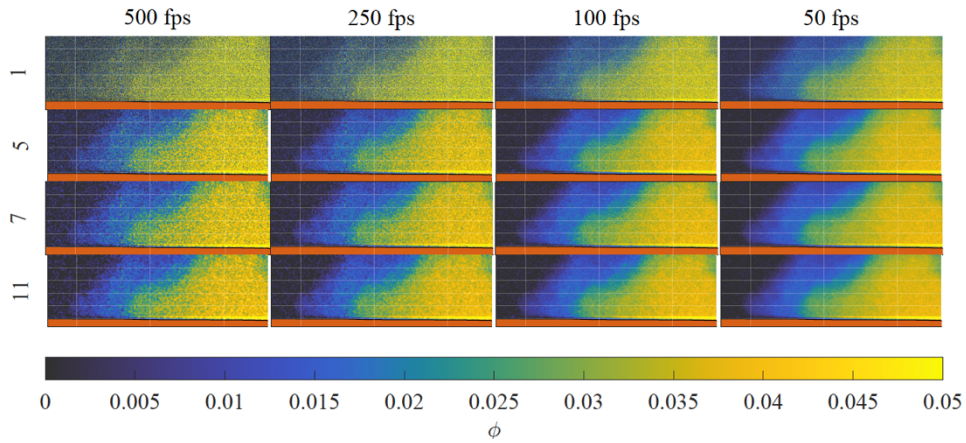


Figure 4: Effect of spatial and temporal averaging on the instantaneous volume fraction field of a lock-exchange turbidity current.

4. Conclusions

In this work, time-resolved photon-counting X-ray densitometry is employed to examine two-dimensional particle-laden liquid flows. The technique demonstrates strong capability for studying flows such as gravity currents and turbidity currents by providing accurate, time-resolved measurements of the density field. This level of resolution allows detailed investigation of key physical processes, including entrainment, particle settling, erosion, and internal flow structure. Although particularly well suited to flows with small density contrasts, the method is best applied to configurations in which variations along the third spatial dimension are minimal.

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