PARTICLE-LADEN SONIC CO_2 JETS: INVESTIGATION OF INITIAL PARTICLE DISTRIBUTION AND TURBULENT SHEAR AGGLOMERATION

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Abstract The characteristics of the particle distribution in a sonic jet release of carbon dioxide (CO_2) from a high pressure reservoir are investigated. The motivations are to quantify the hitherto unknown particle distribution immediately after the Mach shock and examine the level of agglomeration in the jet post-Mach shock. These releases are designed to be representative of a sonic release into the atmosphere and so provide data to help interpret how accidental or deliberate releases from the carbon capture and storage (CCS) chain might behave. We discuss the experimental results in comparison with numerical work, focusing on implementing the initial particle distribution and reproducing the observed agglomeration in a Reynolds-averaged Navier-Stokes numerical model with an adaptive grid, and in terms of the particle distribution function, Lagrangian particle tracking and turbulent shear agglomeration.

INTRODUCTION

Predicting the correct fluid phase and solid particle behaviour during the discharge process in the near-field of sonic CO_2 jets is of particular importance in assessing the risks associated with carbon capture and storage schemes, given the very different hazard profiles of CO_2 in the gaseous and solid states. The initial particle size formed in releases from the liquid phase at high pressure and temperature is unknown. Large-scale experiments and accompanying simulations have indicated that agglomeration is occurring along the sonic jet formed following a free release into the atmosphere. This work was commissioned by National Grid as part of the COOLTRANS research programme in order to experimentally investigate the particle size distribution and agglomeration. National Grid has initiated this programme to address knowledge gaps relating to the safe design and operation of onshore pipelines for transporting dense phase CO_2 from industrial emitters in the UK to storage sites offshore.

EXPERIMENTAL MEASUREMENTS

The experiment was conducted in a laboratory setting in a large container with a separate vent system fitted to ensure safe handling of the CO_2. A 20ml canister of liquid CO_2 was pressurised to 68.9bar and allowed to equilibrate to ambient temperature for one hour. The canister was then clamped into a frame with the nozzle protruding into a custom-made Perspex box (50×50×500 mm), flush with the internal surface of the box. Two custom-made nozzles were used with diameters of 0.5mm and 1mm. The instrument used for measurement was a Dantec fiberflow laser Doppler anemometer (LDA), with a Dantec classic phase Doppler anemometer (PDA) module. The data were processed using a Dantec burst spectrum analyser and Dantec BSA flow software. The illumination was provided by a Spectra-Physics Stabilite 2017 multi-spectral argon-ion continuous wave laser. The LDA was initiated and the measurement volume was located in line with the centre of the jet, at a range of distances from the nozzle, measured in nozzle diameters. Data collection was commenced and 10 seconds later a 1/4 turn gas valve was opened to release the CO_2 from the canister into the Perspex box. Each experiment was released into the atmosphere in the container, mimicking a discharge into a regular atmosphere. The base case employs a 0.5mm diameter nozzle, with measurements obtained at 6, 10, 20, 30, 50, 100 and 150 diameters (D) downstream. A 1mm diameter nozzle was also used, with measurements obtained at 3, 5, 10, 20, 30, 50, 100 and 150 D.

NUMERICAL PREDICTIONS

The numerical technique described in [1] was used to predict the resulting flow, in combination with a particle distribution function and Lagrangian particle tracker. The conditions in the jet were simulated linked to a turbulent shear agglomeration model based on the work of Saffman [2] in order to model agglomeration along the jet.

RESULTS AND DISCUSSION

The experiments have shown that the initial particle distribution post Mach shock is nozzle size independent and centred on a diameter of 1 to 2 micrometres (Figure 1a), in agreement with Weber number predictions. Whilst 80% of the particles have a diameter of 10 micrometres or less, there is an extended population of particles at larger diameters indicating a large-diameter-skewed log-normal distribution after the initial expansion from the nozzle. This directly provides an initial particle distribution function that can be used in safety studies, for example in simulations of dense phase, accidental CO_2 releases from high pressure pipelines. This description can be imposed immediately post-Mach shock in the flow. The experiments have also shown that agglomeration is likely to be occurring along the jet in the 1mm diameter release (Figure 1c), as indicated by the reduction in height of the peak of the particle distribution function at low diameter and the increasing volume under the curves at larger diameters, i.e. there are relatively fewer particles with smaller diameters and relatively more particles with larger diameters at increasing distance from the Mach shock. This does not appear to be the case in the 0.5mm diameter release (Figure 1b). A turbulent shear agglomeration model according to Saffman [2] is able to reproduce the observed agglomeration along the jet in the 1mm diameter nozzle case (Figure 2).

References

[1] C. Wareing, R.M. Woolley, M. Fairweather and S.A.E.G. Falle, 2012, RANS Modelling of Sonic CO_2 Jets, *Proceedings of the 7th International Symposium on Turbulence, Heat and Mass Transfer, Palermo, Italy, 24th-27th September 2012*, Hanjalic, K., Nagano, Y., Borello, D., and Jakirlic, S. (Eds.), Begell House Inc., New York, 349--352, 2012.

[2] P.G. Saffman and J.S. Turner. On the collision of drops in turbulent clouds. *Journal of Fluid Mechanics* **1**:16-30, 1956.

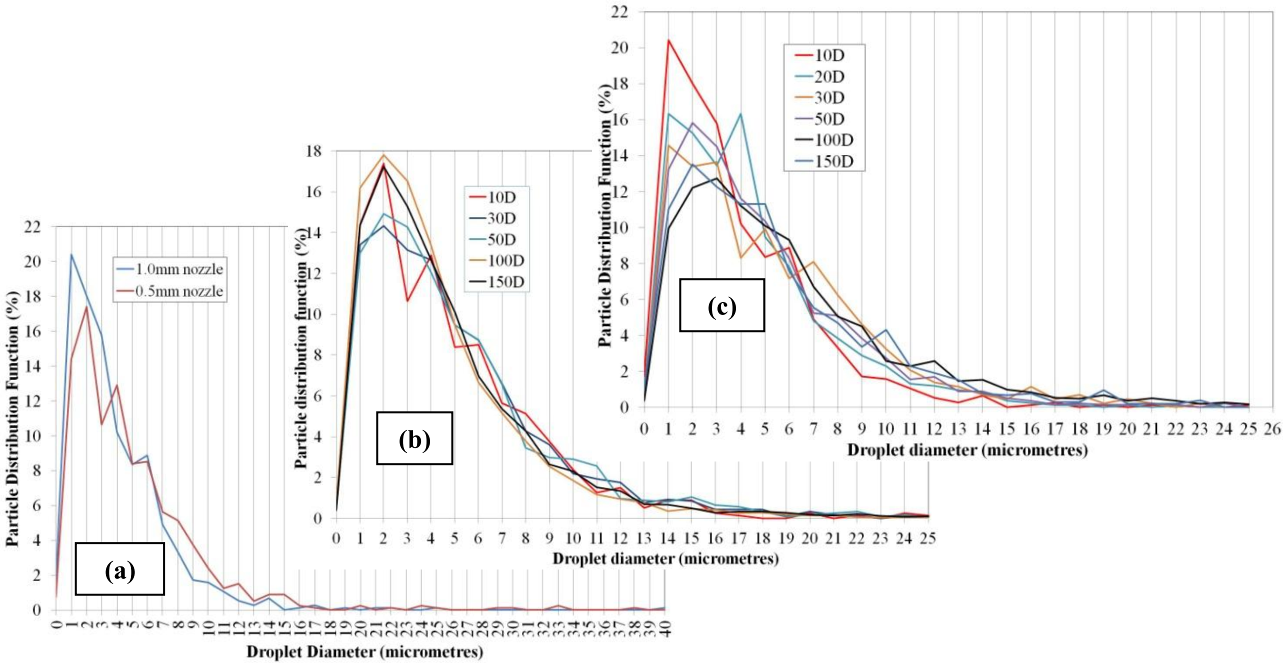

Figure 1. Experimental results. The particle distribution at 10D post Mach shock (a) and particle distribution functions at varying distances along the jet for the 0.5mm diameter nozzle (b) and the 1mm diameter nozzle (c).

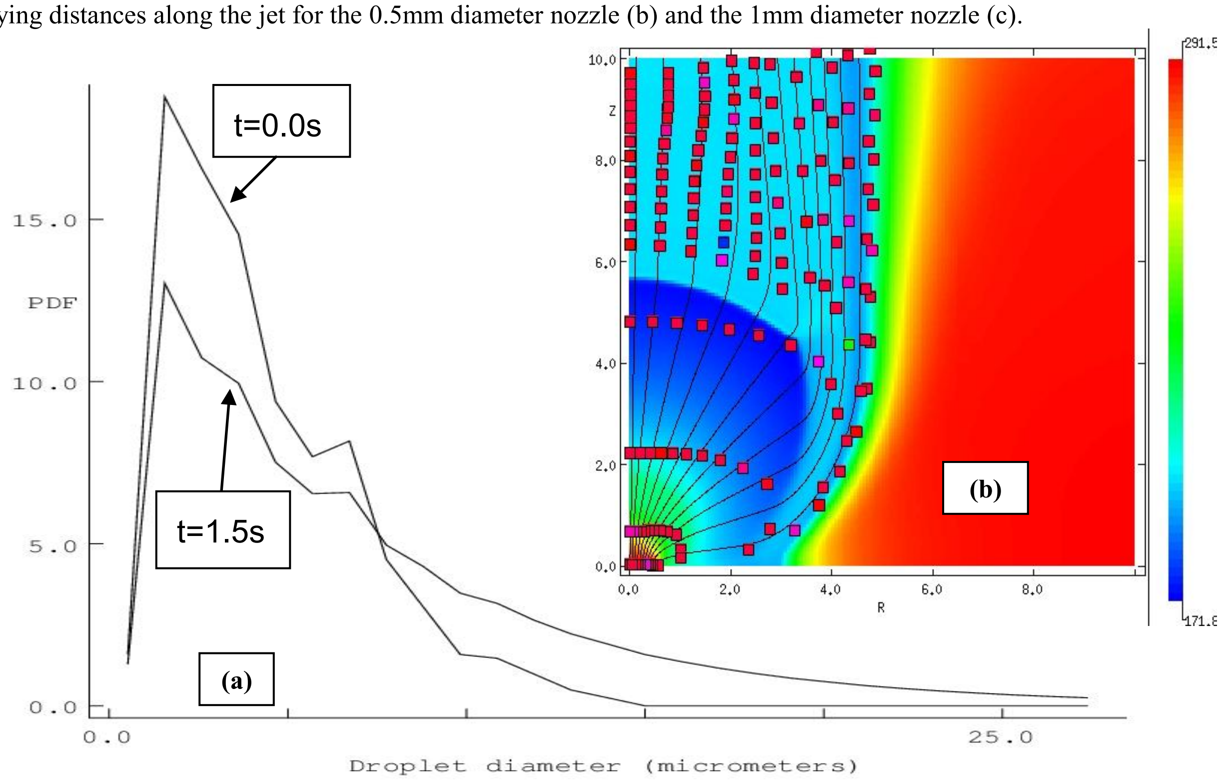

Figure 2. Numerical predictions. (a) Turbulent shear agglomeration according to Saffman [2] used to model the experimental results (initial condition shown at t=0 and agglomerated distribution at t=1.5s) and (b) axisymmetric temperature predictions of the near-field Mach shock structure with stream lines and particles positions (squares).