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Advancing PDC Hazard Modelling: Benchmarking Pyroclastic Density Current Models Against Large-Scale Experiments

Pyroclastic Density Currents (PDCs) are the most deadly of all volcanic hazards. An international consortium of volcanologists has used the computational power of ARCHER2 to run high-resolution PDC simulations using data captured from a state-of-the-art experimental facility in New Zealand.

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Abstract

Imagine a furious torrent of superheated gas, ash, and rock cascading down a volcano at hurricane speeds - this is a Pyroclastic Density Current, both immensely fascinating and devastatingly dangerous. Despite being one of the deadliest aspects of volcanic eruptions, our understanding of PDCs and our ability to predict their path of destruction remains shrouded in uncertainty. Ensuring the safety of communities living in the vicinity of volcanoes necessitates the accurate forecasting of where these deadly flows will travel. While technological advancements have enhanced our modelling capabilities, validating the accuracy of these models has proved to be a formidable challenge. Over the past decade, a consortium of international volcanologists has united, harnessing the power of a state-of-the-art facility in New Zealand to rigorously test the most advanced PDC numerical models. This pivotal research has not only highlighted the limitations of our current understanding but also shone a light on the critical parameters that must be meticulously measured in future experiments and natural events. Ultimately, our collective knowledge and collaborative efforts pave the way towards the development of models that can reliably predict the terrifying journey of these lethal volcanic phenomena.

Shiveluch volcano eruption from 2023

NASA Earth Observatory

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Benchmarking Exercise

The inherently fatal and devastatingly explosive nature of Pyroclastic Density Currents (PDCs) has long shielded their internal properties from scientific scrutiny. The internal dynamics of these ferocious natural phenomena had remained shrouded in mystery, forcing volcanologists to develop innovative experiments.

In 2013, a groundbreaking venture into the turbulent world of pyroclastic density currents (PDCs) unfolded. Dr Eric Breard and Prof Gert Lube embarked on the first large-scale flume experiments (dubbed PELE, Figure 1) involving natural volcanic mixtures, presenting a daring glimpse into the internal workings of these catastrophic volcanic phenomena. Experiments involved creating a collapsing mixture of heated volcanic ash and rocks, designed to simulate the collapse of a volcanic column on a slope, providing invaluable insights into the enigmatic behaviour of PDCs. A decade followed, rich in experimental exploration and discoveries, significantly broadening our fundamental grasp of PDC dynamics. The revelation of their internal structure, the crucial role of particle clusters in influencing ash settling and runout, and the mechanism prompting the self-fluidization of the dense basal layer—which astonishingly behaves like a fluid—were among the key findings. Additionally, the self-organizing nature of the ash-cloud into turbulent eddies unexpectedly created large pressure fluctuations, far exceeding prior estimates.

Figure 1: Side view of the PELE experiment, where an infrared image is overlaid on the visible image. The flow is 2m high on the left side of the picture.

Faced with the uncovered complexities, a pressing question loomed: how accurately could our existing numerical PDC models mimic these flows? A collaborative benchmarking exercise, designed alongside colleagues from INGV Pisa, sought to answer this by producing experimental flow data to rigorously test a spectrum of numerical PDC models—from simplified 1D versions to advanced 3D multiphase flow models—bridging the gap between experimental observations and predictive capabilities.

3D numerical modelling of PDCs

Diving into the numerical realm, we adapted an open-source tool named MFIX, originally written by the US Department of Energy, tailoring it into a simulator of volcanic processes. Using invaluable data harvested from our large-scale PELE experiments, we mirrored these monumental flows in a virtual environment, precisely replicating the experimental conditions. These extremely computationally expensive simulations were only feasible thanks to ARCHER2's computational resources. These high-resolution (down to 2 cm) and high-frequency simulations (capturing data at >1000 Hz) offered us a meticulous lens through which we could scrutinize the robustness of the physics implemented in multiphase PDC numerical models, aiming to test our ability to capture their inherent complexity (See Figure 2).

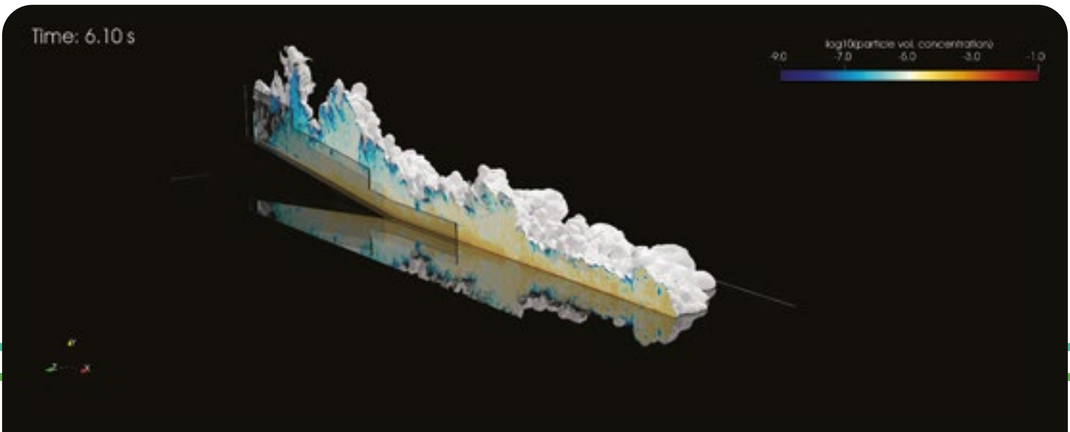

Figure 2: Large-Eddy Simulation of a pyroclastic density current reveals a vertical slice of particle volumetric concentration along the flow's centre line. The white surface, halved for clarity, outlines the flow's boundary.

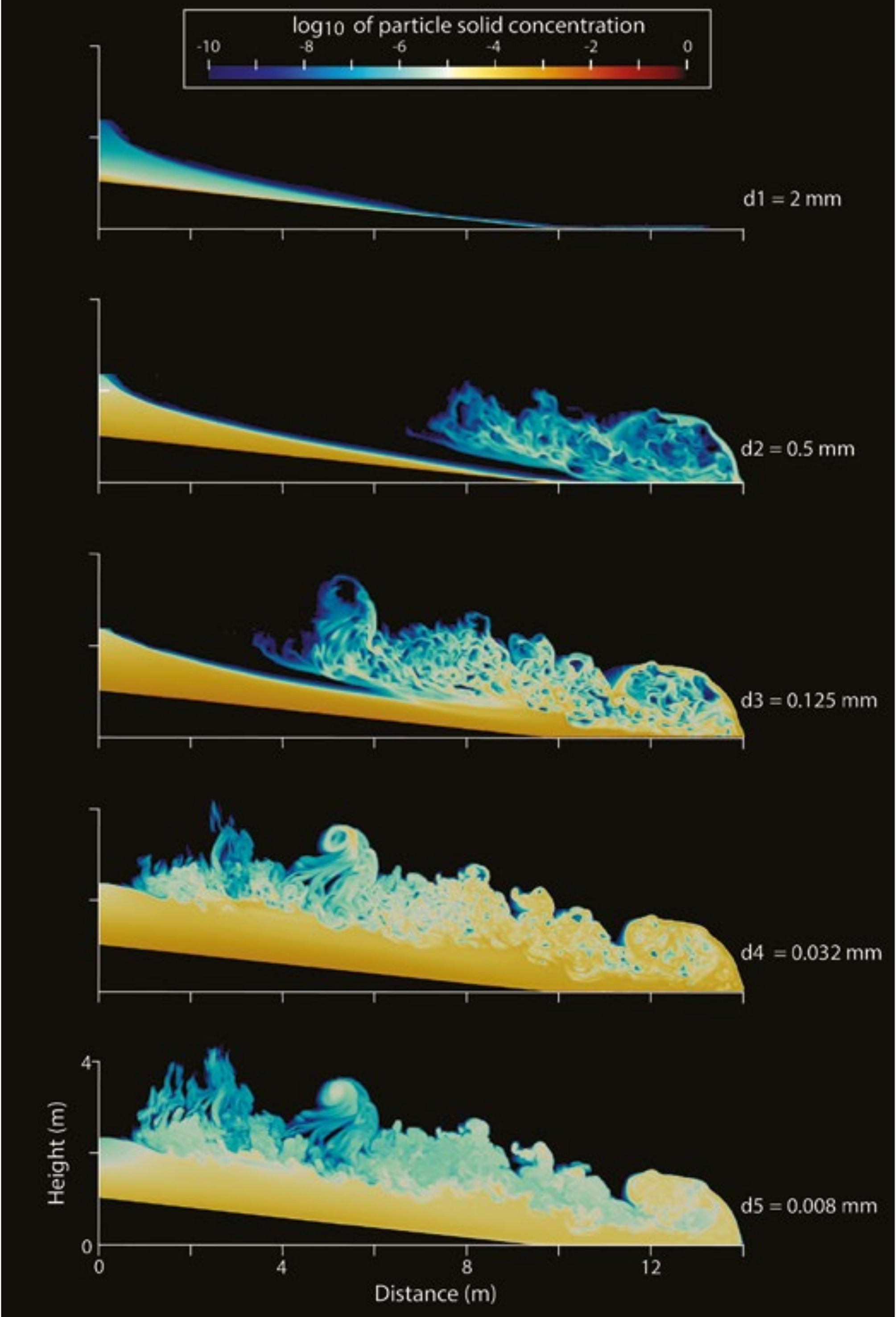

Figure 3: Slices through the 3D numerical simulation showing the particle volumetric concentration of various particle sizes (from 2mm to 8 microns), illustrating the range of various degrees of coupling between the turbulent eddies and the particles.

A key revelation was the necessity of a precise 3D model of the flume to accurately mimic the experimental flow, especially to encapsulate the ambient air's entrainment within the hot mixture. Furthermore, our findings illuminated that simulations are markedly sensitive to a particular input: the particle volumetric concentration. Intriguingly, this parameter, notorious for its measurement challenges in gas-particle experimental flows among volcanologists and engineers, emerges as a pivotal focal point for future advancements in sensor technology and deployment within natural flows.

Harnessing the formidable power of ARCHER2, we delved into the enigmatic world of gas-particle interactions within these volcanic flows, carrying out simulations that embrace a highly diverse range of particle sizes—what we call 'highly polydisperse multiphase flow simulations'. As captured in Figure 3, particle size plays a pivotal role in determining how long they remain transported by turbulent eddies and whether they will settle to form a dense, flowing layer at the base, or continue to be suspended in the turbulent mixture above. One of our key experimental findings—a unique regime where mutual gas-particle interactions lead to the formation of particle clusters, enhancing their settling—are well replicated in these simulations, as seen in Figure 3.

The success of our 3D benchmarking work unveils a realm of possibilities for the MFIX solver. In synergy with the unparalleled computational power of ARCHER2 HPC, we are now confidently equipped to simulate PDCs traversing actual volcanic landscapes, transforming this digital tool into a formidable asset for enhancing our preparedness and mitigating the volcanic hazards posed by pyroclastic density currents.

Mount Sinabung, Indonesia 2016

Yosh Ginsu

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About ARCHER2

ARCHER2 is the UK's National Supercomputing Service, a world class advanced computing resource for UK researchers. ARCHER2 is provided by UKRI, EPCC, HPE and the University of Edinburgh. ARCHER2 is the latest in a series of National Supercomputing Services provided to UK researchers.

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