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Design and Optimisation of a Powder Feed System for In-Space Additive Manufacturing

Final Presentation

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Hi everyone and thank you for coming to my presentation on my final year project looking at “Design and Optimisation of a Powder Feed System for In-Space Additive Manufacturing”.

During this project, I designed, built, and experimentally characterised a powder feed system. Focusing on aspects of the subsystem like robustness in the face of microgravity and control of powder mass flow rate.

Agenda

1. Motivation & Objectives
2. Background
3. Design Solutions
4. Experimentation
5. Numerical Simulations
6. Conclusion & Future Work

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In this presentation, I'll start by briefly outlining the motivation behind the project and the potential benefits of in-space manufacturing. Then I'll cover some of the key physics that influenced the design choices, followed by the designs themselves.

After that, I'll walk through the main experiment and its results, touch on the numerical analysis, and finally wrap up with conclusions and suggestions for future work.

So, why In space manufacturing? Well, space offers a set of unique conditions—like microgravity and vacuum—that are very expensive to achieve on earth. Therefore, certain products, like semi-conductors or nanomaterials, could be made at a higher-quality and lower-cost than their terrestrial competitors.

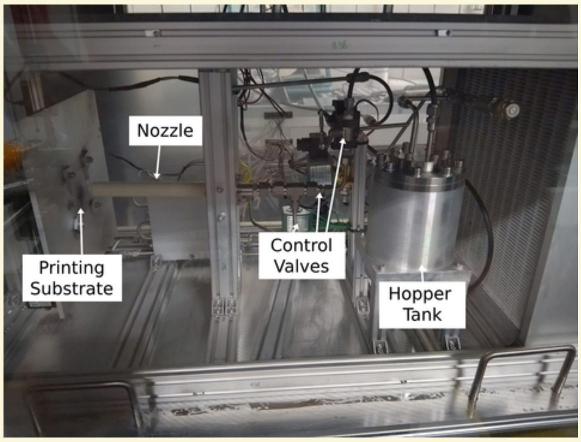
Additive manufacturing, in particular, is well suited to supporting space missions. Parts too big to fit into launch vehicle fairings or replacement components could be manufactured on demand where they are needed. This would lower launch costs, lengthen satellite lifetimes and add much needed redundancy to future scientific missions.

This possibility has already been identified by both NASA and ESA who have produced plastic and metal 3D printed pieces in the international space station. Both experiments used wire feedstock, and to unlock the full range of additive manufacturing methods, reliable powder feed systems need to be developed.

Motivation

Current line of research

- **Review of Additive Manufacturing Methods**
- **COSMOS Demonstrated Cold Spray under Vacuum**



COSMOS Setup in Hypersonic Lab

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This line of research started with a review of different additive manufacturing methods and their suitability for the space environment. Despite the requirement to bring a propellant gas into orbit, Cold Spray was identified as a strong candidate for space use. It has a high deposition rate, requires minimal post-processing, and can print onto unprepared surfaces.

Building on this report, a project called COSMOS, led by Dr Panesar, successfully demonstrated cold spray additive manufacturing in a high vacuum. COSMOS provided strong evidence for the suitability of the cold spray method in space but also highlighted areas for optimisation, particularly around powder feeding rate and powder management under microgravity.

Therefore, to ensure more certainty in translating the design into the space environment, this research aims to align the system more closely to the conditions being emulated.

Objectives

- **Investigate Hypothesised Issue with Current Design.**
- **Design New Feed System to Adress Previous Issues.**
- **Characterise Controllability of Mass Flow Rate.**
- **Investigate Impact of Piston Geometry on System Dynamics.**
- **Numerically Simulate Design in Microgravity.**
- **Numerically Simulate Design in Terrestrial Conditions.**
- **Analyse if Results Validate Translation to Space Environment.**

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To do this , seven key objectives were identified.

The first was to investigate the hypothesised issues with the existing powder feed system, which due to time constraints, won't be covered today.

Assuming the need for a redesign was validated, the next objective was to design a fluidising powder feed system as well as a piston to constrain the powder. Focusing on controllability of mass flow rate and the implications of microgravity.

Following the design and manufacture of the system, the aim was to experimentally characterise the consistency and controllabiltiy of the mass flow rate.

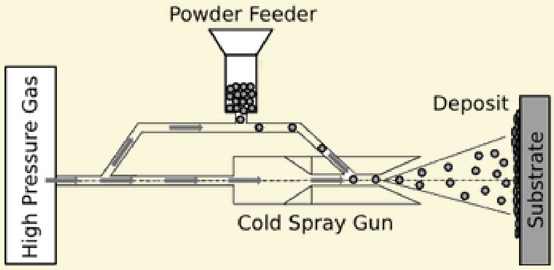
To support this analysis, numerical simulations were planned — both with and without gravitational forces — to better understand system performance in space conditions.

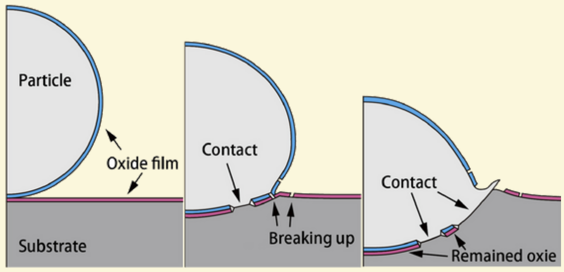
The final objective was to assess whether the experimental results could validate the terrestrial simulation, and whether that in turn could support the extrapolation of results to a microgravity environment.

Background

Cold Spray Method

- **Solid-State Deposition**
- **Particle Deforms on Contact**
- **Bonding Through Cold Welding**





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To better understand the shortcomings of the previous testing, knowledge of the cold spray process is required.

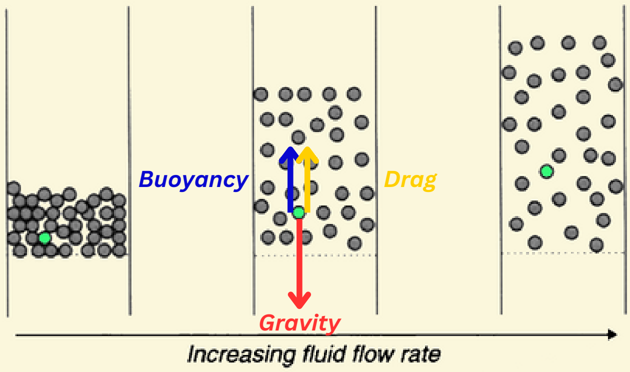
This method works by accelerating metal powder particles to supersonic speeds so they impact and bond with a substrate through cold welding. The bonding happens because the particles deform on impact, stripping away oxide layers and exposing clean metal surfaces.

If the ratio of metal powder to accelerant gas is too high, as was hypothesised in the previous system, each individual particle will reach a slower maximum speed, therefore, not deforming as required or bonding as strongly and resulting in the high porosity deposit achieved.

Background

Powder Fluidisation

- Two-Phase Flow
- Suspended Particles
- Force Balance
- Fluidic Behaviour



Gibilaro, L.G. (2001) Fluidization-dynamics: the formulation and applications of a predictive theory for the fluidized state.

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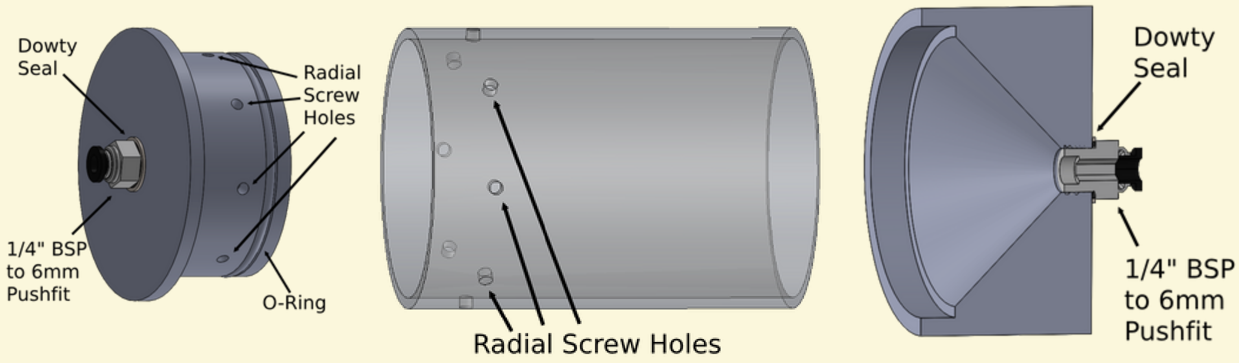
Given that cold spray already requires the manipulation of powder using high speed flows, it is efficient to use fluidisation to control the powder dispensing.

Fluidisation occurs when a gas is passed, usually upwards, through a powder and causes the particles to become suspended. The drag from the gas balances out the weight of the particles and causes the bulk powder to expand and flow like a fluid. Of course, in microgravity there is no weight for the drag to counteract but it was assumed that other forces, like cohesion, would perform the same function as gravity. However, little literature exists on this topic to validate the assumption.

Design Solutions

Tank Design



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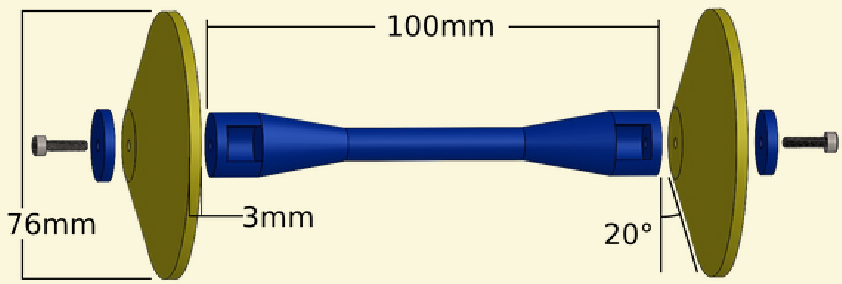
The architecture chosen for the feed system is known as a fluidising powder bed and works by holding the powder in a cylindrical tank near the end, then passing gas from the inlet to entrain particles out of the system.

The tank made for this design consists of 3 parts. The two Delrin end caps and the acrylic tube for the walls which was chosen as transparent to allow for recordings of the flow behaviour.

As you can see, the inlet end cap was radially screwed to the tube to allow it to be removed to test different piston designs.

Design Solutions

Piston



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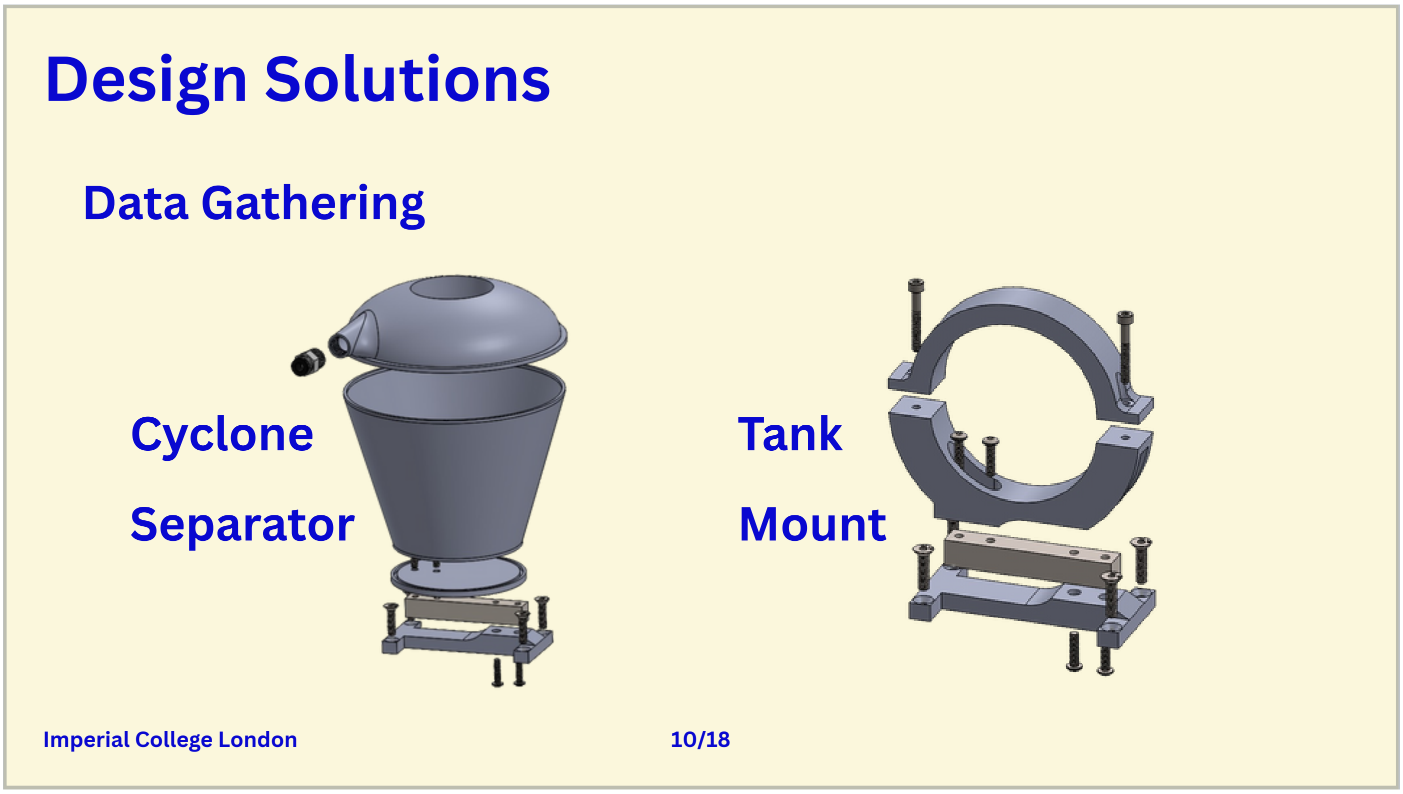
In the tank, between the inlet and the powder, there is a piston. Its role is to compact the powder to the outlet, preventing disruptions in feed rate due to inconsistent distributions of particles within the tank. A pneumatic gas-permeable design was used and functions by generating a pressure differential across the two faces which forces it forwards into the powder.

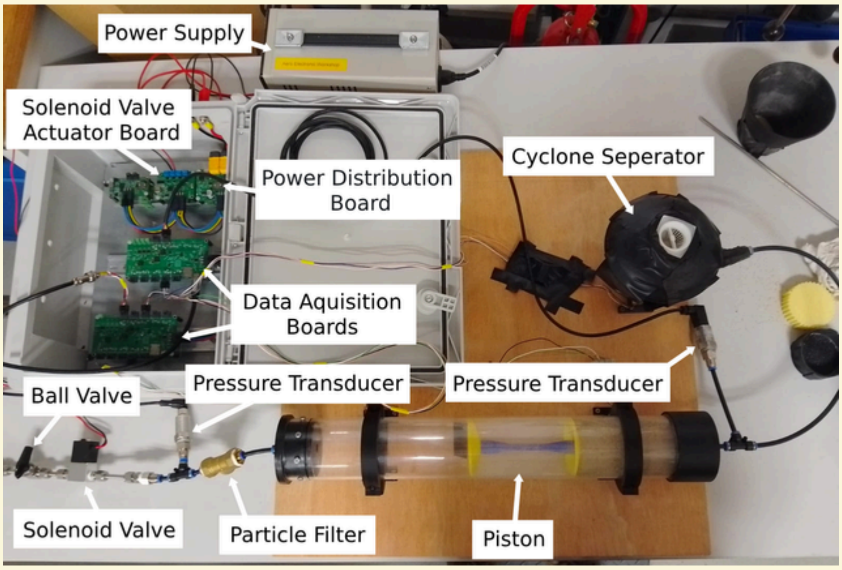
After an iterative design process, the final design uses two flexible TPU cones connected by a PLA rod. This minimised the chance of jamming while allowing for large pressure differentials to be generated resulting in more reliable powder compaction.



The final part of the experimental set up is recording the mass flow rate. During operations, the powder is expelled from the tank and is captured by a cyclone separator. This is done to ensure the powder is separated from the gas and contained so that it doesnt become airbourne. To track the rate in which the powder was transferred out of the system, mass measurements of the tank and of the powder within the separator were recorded.

On the left is the cyclone separator and it held the dispensed powder, on the right is one of the two brackets that held the tank and the readings from the two brackets were combined to find the mass of the tank over time.

Experimental Setup



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This is the configuration of the experiment stopped half way through testing. The data acquisition electronics can be seen in the top left and the compressed air line supplies gas into the system at the bottom left.

The gas flows through the valves and into the tank, pushing the piston and fluidising the powder. The sand is then expelled into the separator and the mass changes are recorded.

Key Results

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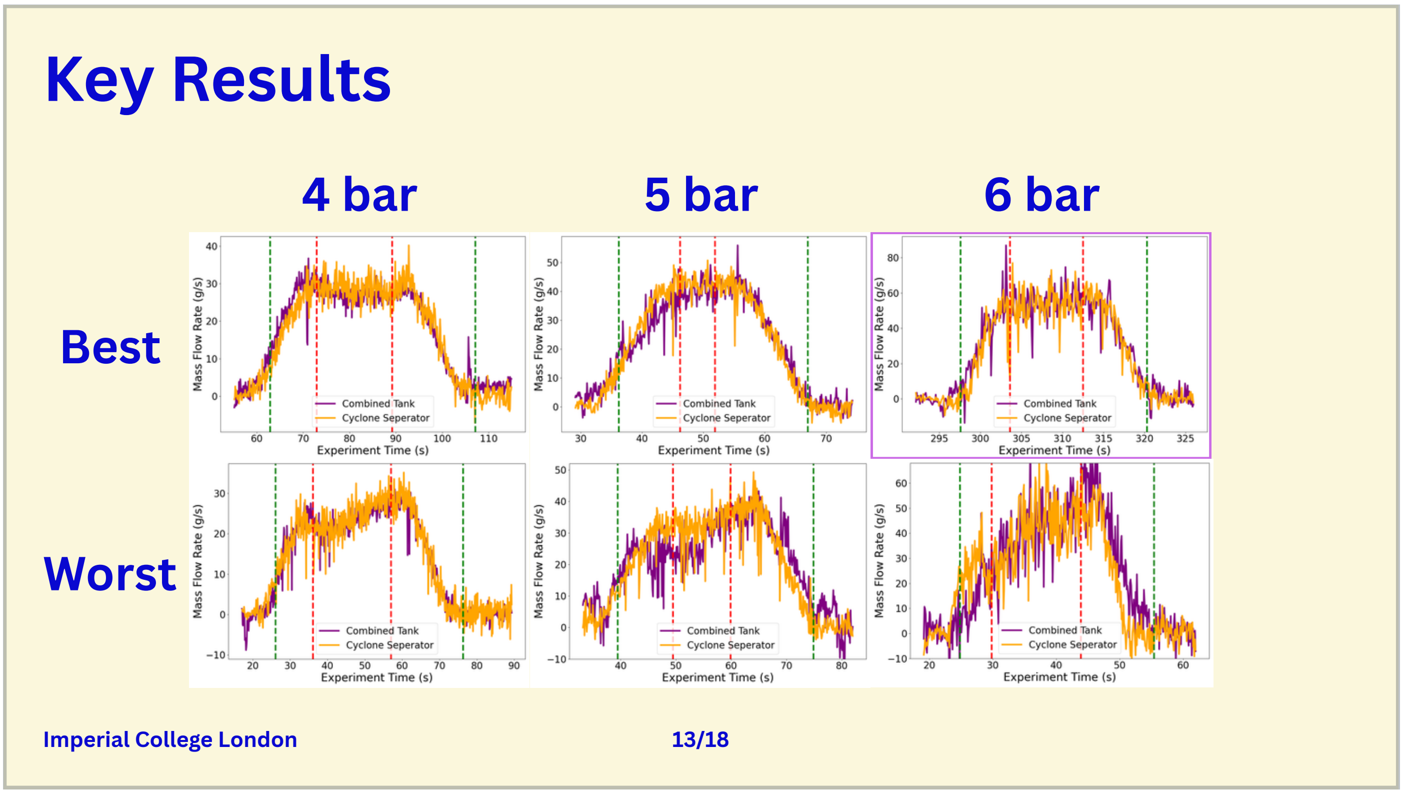
The best way to understand the results is through a video of one of the tests. As there were 3 unexpected transient behaviours.

The first being at the start of the video, you can see that the powder close to the piston appears to become fluidised. This contrasts the theorised behaviour where the fluidising region remains close to the outlet.

The next thing to note is the jerky motion of the piston. Previous work used the reliability of the piston’s smooth motion to measure the mass flow rate but this isnt seen.

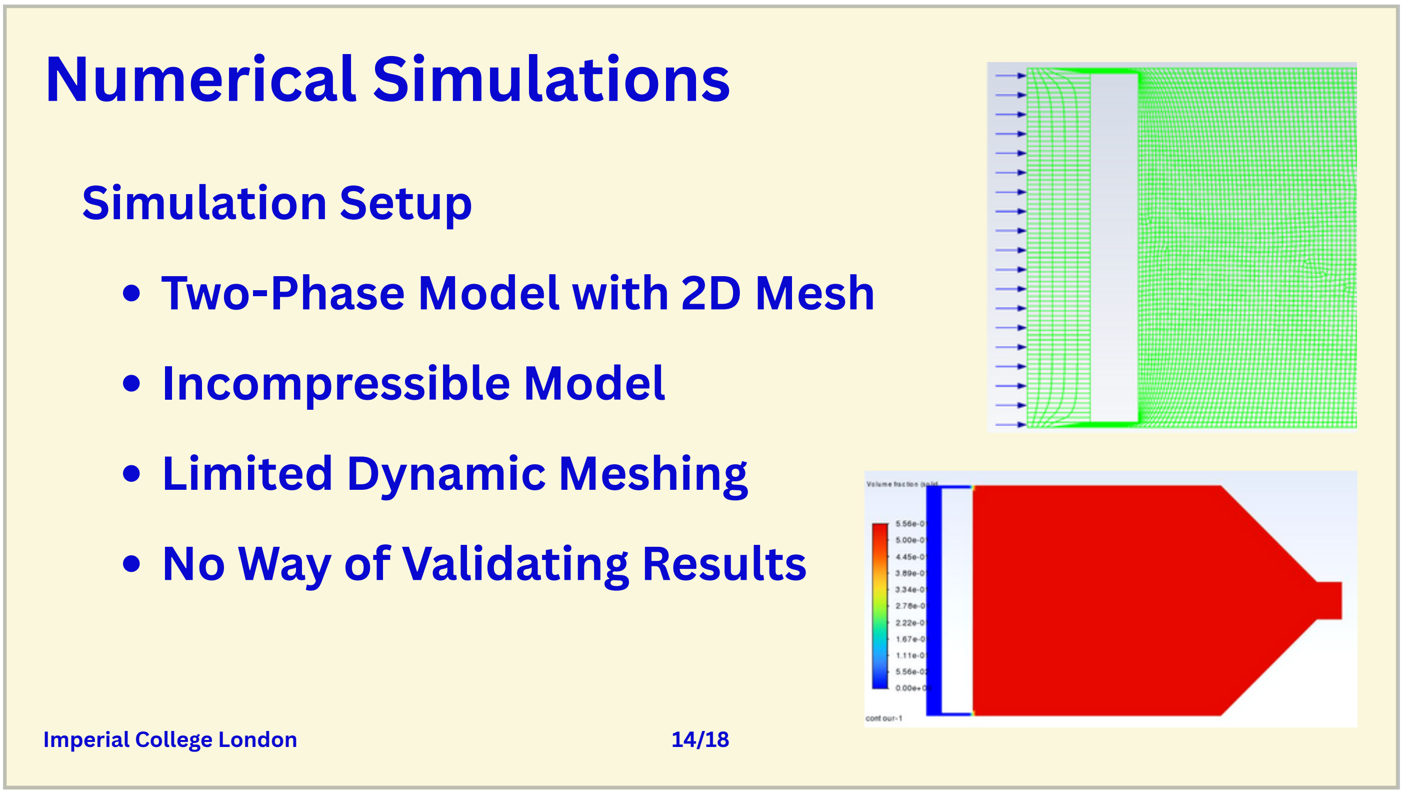
Finally, the bulk powder region appears to go through discrete rearrangements which was expected to impact the quality of mass flow rate.



As you can see however, the piston's jerky movements and powder behaviour don't noticeably affect the measured mass flow rates. The data shown here is from six of the nine tests, with the purple trace corresponding to the one just demonstrated.

The first thing to highlight is the remarkable consistency seen in some of the tests. This is a promising result, as consistent mass flow is essential for producing high-quality cold spray deposits, and it speaks to the potential of the fluidised bed architecture. That said, other tests show much greater variability, indicating that further tuning of the system is still needed.

Interestingly, the mass flow rates observed here are several orders of magnitude higher than those reported in previous studies. This is likely due to the decision to remove the system's choke point to avoid clogging during testing. While this limits direct comparison, it does demonstrate that much higher flow rates can be achieved with lower inlet pressures—potentially reducing the amount of gas required to run a cold spray system.

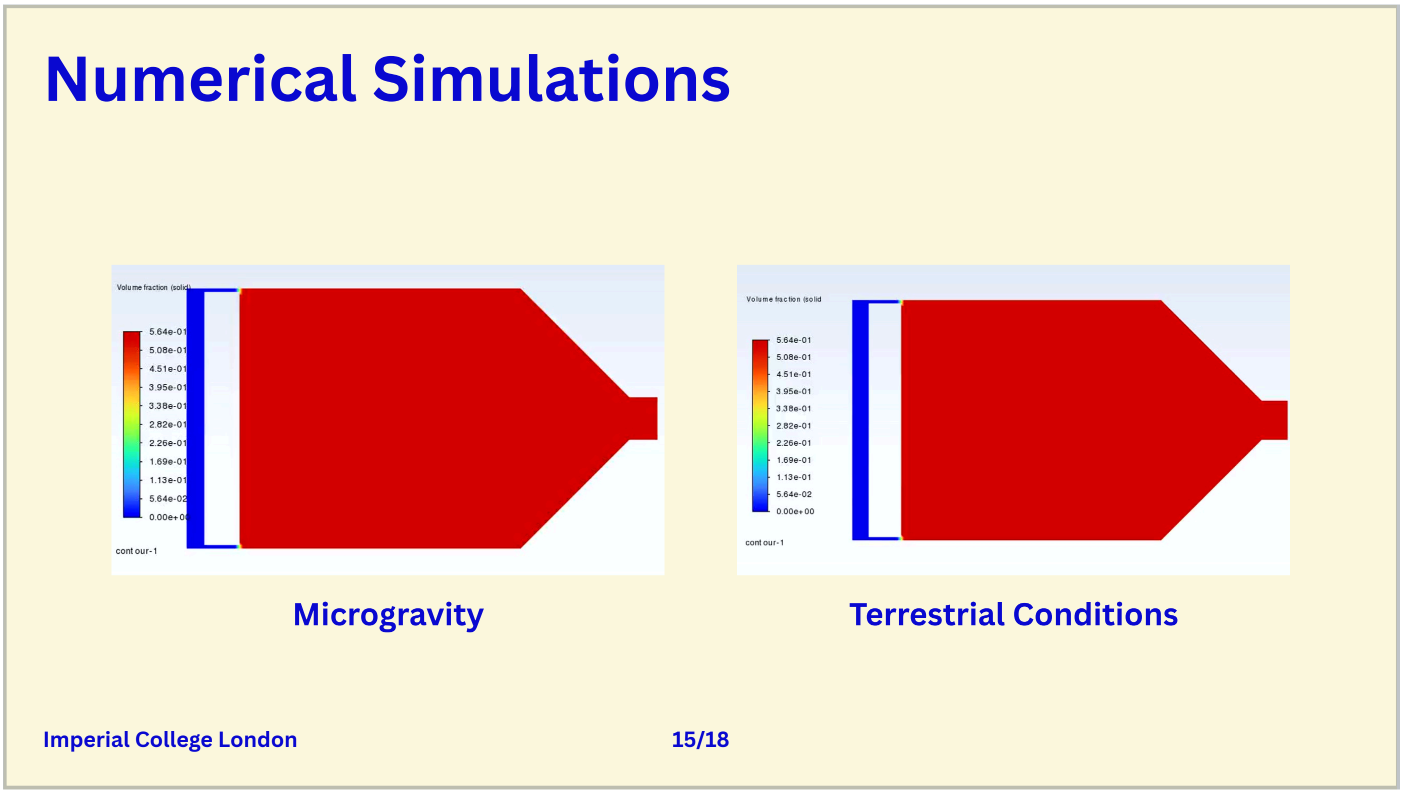


To support the experimental investigation of the system, numerical simulations of a simplified system were conducted. The goal was to correlate the results of the experiment with numerical simulations under terrestrial conditions and then use the same setup to investigate its behaviour under microgravity. However, the highly complex nature of the flow pushed this comparison just outside the scope of the project.

Few simulation softwares can investigate flows containing two phases as well as moving meshes so ANSYS Fluent was chosen. This unfortunately came with a number of major limitations.

The first being a limit on the number of cells of the mesh which reduced the analysis to 2D. Additional issues like not being able to use a 2-phase model with a compressible model and limits on remeshing capabilities greatly hindered the progress of the analysis.

Even if all these problems were overcome, there is the remaining issue of experimental data to validate these simulations not existing.



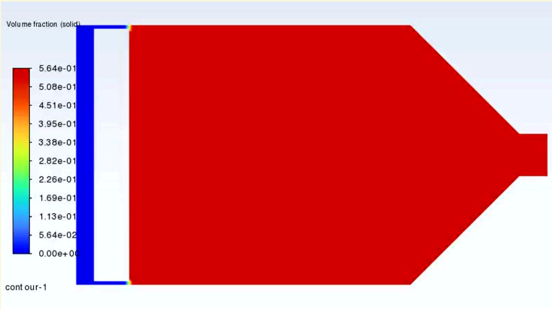
Despite this, the models still produced simulations that appear reasonable. The recordings show the particle density within the system with a piston moving at a constant 90mm/s.

On the left you can see the light orange region and the piston pushing the expanding darker red region. These appear to represent the fluidising and bulk movement regions expected from theory. Close to the 0.2s mark the whole region becomes one homogenous colour as the piston compacts the powder.

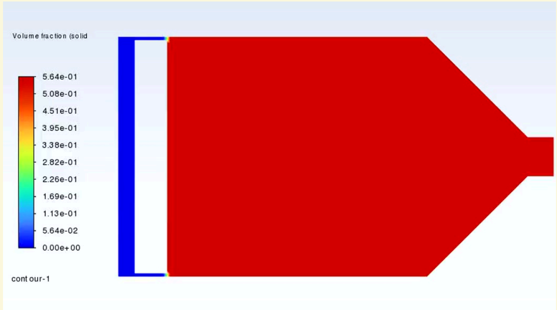
On the right is the same system under gravity, as you can see, there is no difference in density once the powder collects at the bottom. This is expected to be because gravity is playing an outsized role in particle dynamics due to the 2D nature of the flow.

While the microgravity simulations were able to reproduce the relationship between mass flow and piston velocity, given that the simulations under terrestrial gravity dont mirror the experimental behaviour, fewer comparisons can be drawn than initially hoped for.

Numerical Simulations



Microgravity



Terrestrial Conditions

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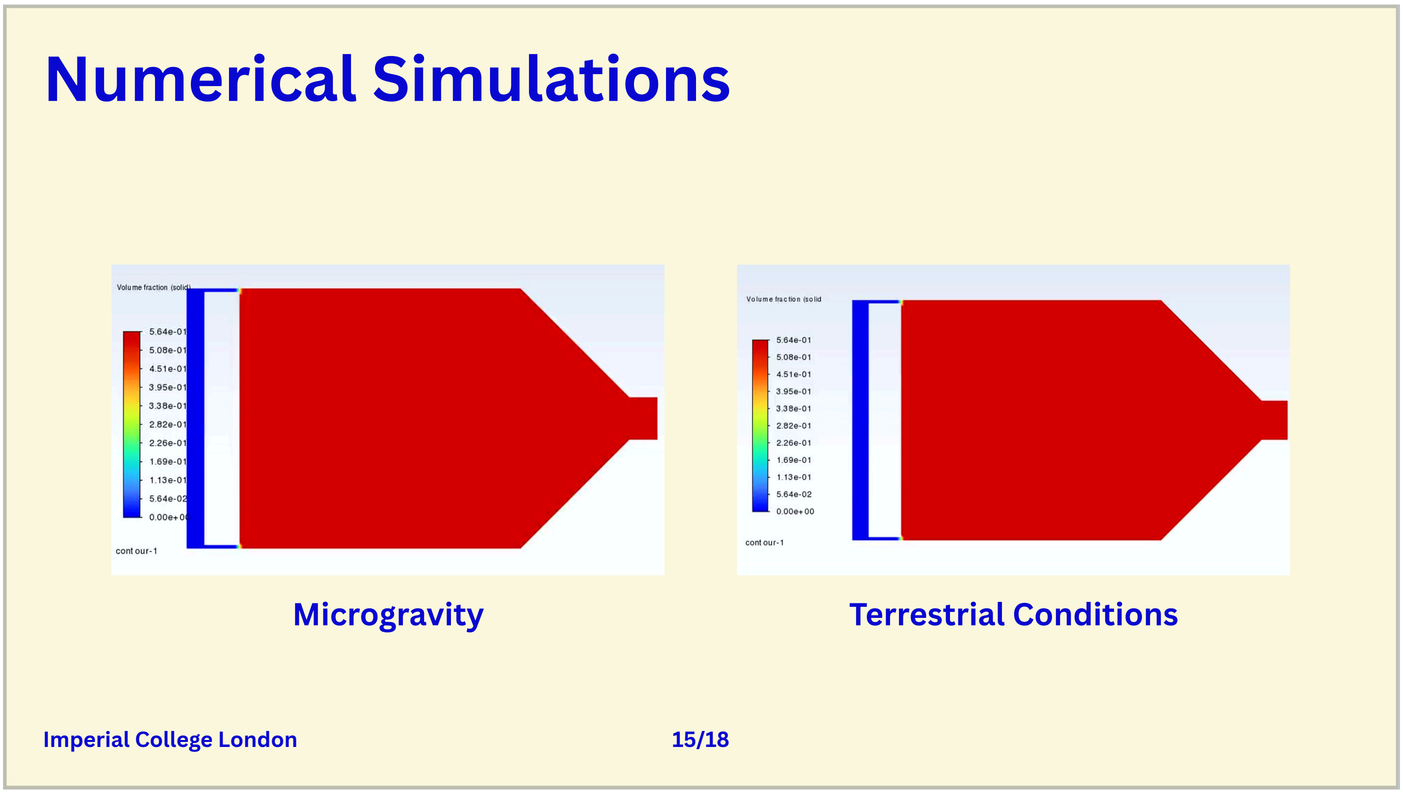

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Numerical Simulations

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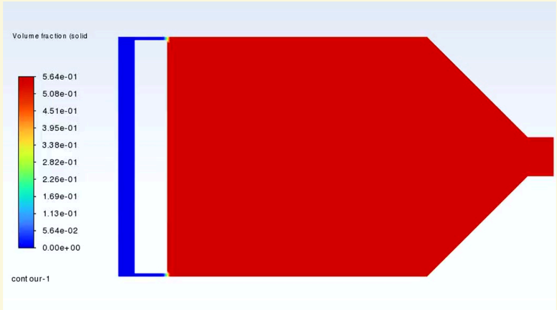

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Conclusion

Main Outcomes

- **A Fluidised Powder Bed Architecture was Analysed**
- **Results Suggest Controllable & Reliable Mass Flow Rate**
- **Novel Piston Geometry was Designed and Tested**
- **No Fatal Flaws were Uncovered in the System**
- **Numerical Simulations were Attempted**

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This project touched on most aspects of designing a system for space applications. in the end provided a promising solution to feeding powder into a cold spray additive manufacturing system.

The mass flow rate data recorded from the prototype suggests that the architecture is controllable and given adequate tuning could produce flow rates reliable enough for high quality manufacturing.

A novel piston design was proposed that overcomes some of the key issues of the piston tank and no major road blocks were uncovered that would guarantee unsuitability for space applications.

On the other hand, no hard evidence for performance of the current design in microgravity was found, but the project still provided a solid foundation for further investigation.

Conclusions & Future Work

Areas for Development

- Reduce Mass Flow Rate
- Use Smaller Powder Size
- Conduct Detailed Analysis of Piston
- Develop More Sophisticated Numerical Simulations
- Test Under Microgravity

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Next steps for the line of research include investigating topics that could only be briefly covered due to the scope of the project.

The first of these involve refining the design to reduce the mass flow rate as well as using finer grain powder. This will align the investigation even closer to that which could be used in an in-space demonstration and reduce uncertainty

Next is analysing the influence of piston geometry and investigating optimisations to either increase quality of feeding or controllability under different gas/powder combinations.

Finally, before justifying an experimental test under microgravity, a more bespoke modelling solution should be conducted to close gaps in research on fluidising powders under microgravity.

Questions?

https://www.digitalalloys.com/blog/cold-spray/

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Thank you for listening to my presentation. I am happy to answer any questions you may have