SPACE STATION ESPRESSO CUP

CAPILLARY EFFECTS OF DRINKING IN A MICROGRAVITY ENVIRONMENT

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Capillary Cup

- The Capillary Flow Experiments (CFE) were a set of fluid physics flight experiments aimed at studying capillary flows and phenomena in low gravity environments.
- A practical application of these experiments resulted in the design of the Capillary Cup also known as Space Cup.

@AstroSamantha - Twitter

Capillary Cup

- On the ISS, NASA astronaut Donald Pettit created the Capillary Cup, a device designed for use in a microgravity setting, and it was inspired by Pettit's wish to sip water in space without using a bag or straw.

The Zero-G coffee cup - YouTube

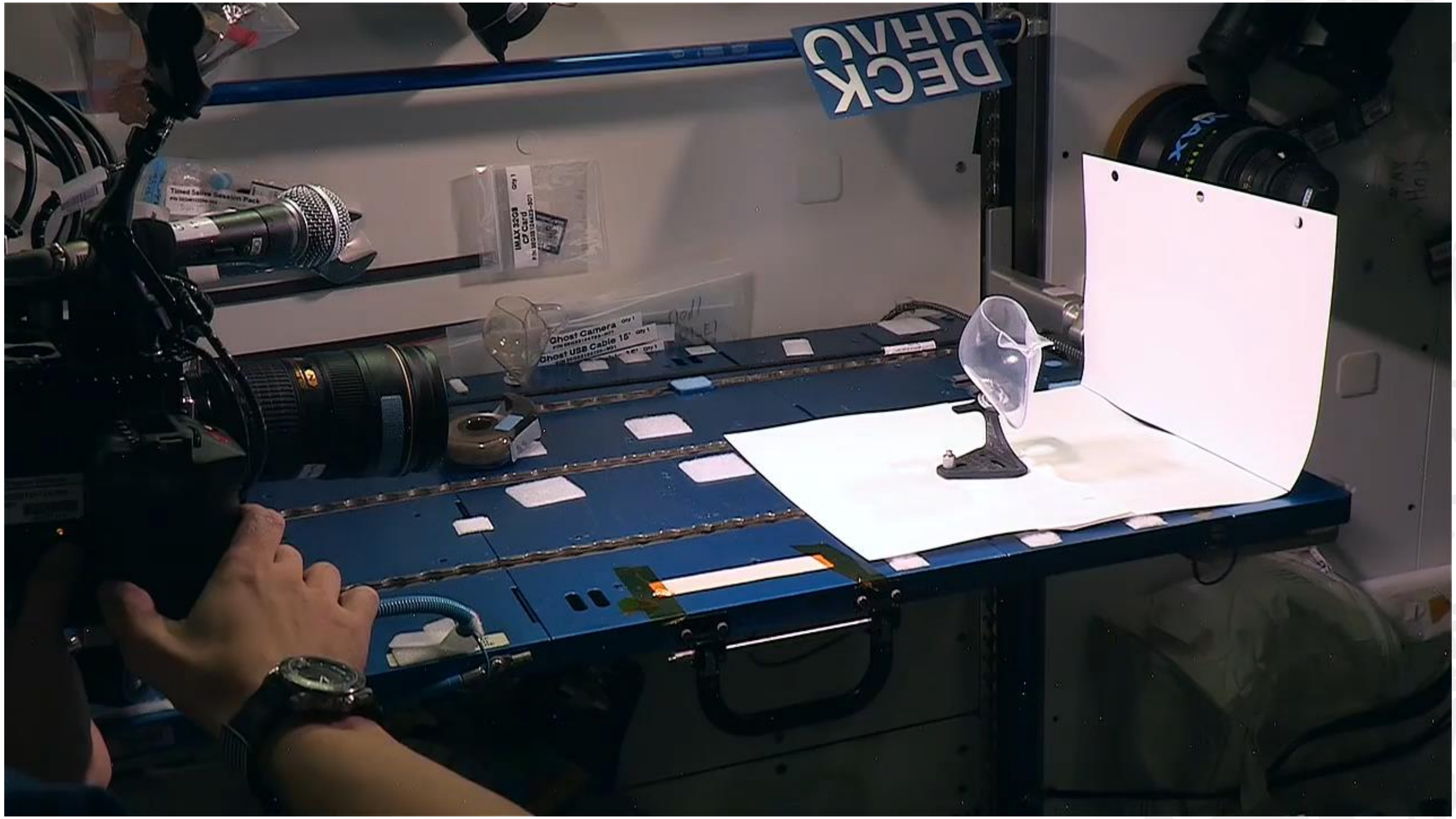
Agenda

1. Experiment Overview
2. Objective
3. Data to be Acquired
4. Requirements
5. Experimental Sequence
6. Deliverables

Experiment Overview

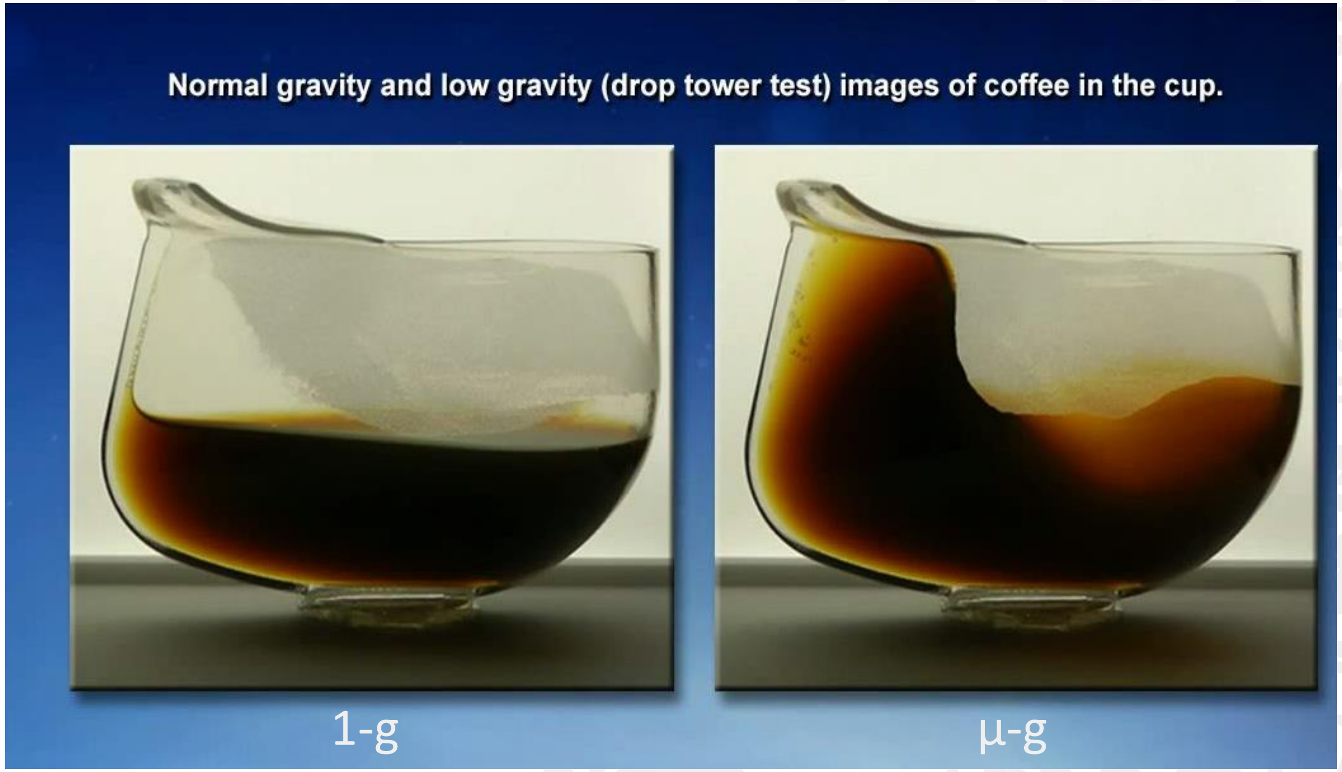
- Rather than rely on gravity, the cup functions in a similar manner to those on Earth, but it uses the combined effects of surface tension, wetting, and cup geometry. A primary science goal of the Capillary Beverage Experiment is to photograph the drinking process comparing the results with predictions that use mathematical and computer models.

Experiment Overview



Experiment Overview

- In 1-g condition (*left picture*), there are no benefit in using this geometry.
- In μ-g condition (*right picture*), the design enables to easily drink from the cup because the beverage is automatically brought to the lip of the mug by the capillary force.



Objective

- Planning and performing an experiment to study the phenomenon of capillarity involving the Space Cup in microgravity conditions using two different liquids.
- Designing a numerical simulation to predict the fluids behavior and to compare them with the experimental data.

Data to be Acquired

- The images captured by the camera during the parabolic flight and, consequently, the time needed by the two liquids in order to reach the highest point possible with respect to the base and to show how capillarity works.

Requirements

- The physical copy of the Capillary Cup that must be watertight.
- Use of a camera in order to record the experiment.
- An aircraft and a pilot capable of performing a parabolic trajectory in order to create microgravity condition onboard of the airplane.
- A suitable experimental platform and a well-designed support capable to withstand all the maneuvers performed by the airplane.
- A laptop with all the CAD, slicing, and CFD software tools needed to perform the preliminary analyses and modeling.
- All the tools needed to assemble the experimental set-up.
- All the tools needed to evaluate a material analysis.

- Hardware Requirements
  - Space Cup
  - Support
  - Platform

Hardware Requirements – Space Cup

- CAD file of the Capillary Cup ✓
- 3D printers ✓
- Dyed Water based solution ✓
- Vegetable oil ✓
- CAD and slicing software ✓
- Cutting tools ✓
- Cyanoacrylate adhesive ✓
- Analytical balance (+/- 0,1 mg) ✓
- Contact Angle System OCA ✓

Hardware Requirements – Support

- CAD software ✓
- Softwood ✓
- Ruler and circular saw ✓
- Adhesive glue for wood ✓

Hardware Requirements – Platform

- GoPro camera ✓
- The plastic platform ✓
- A plexiglass sheet ✓
- LED lamp ✓

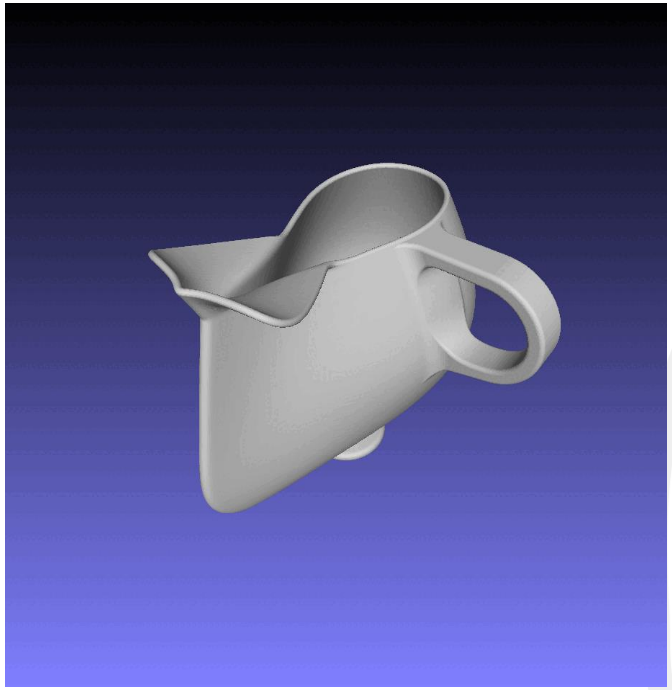
Experimental Sequence – Empiric Simulation

Design the CAD model → 3D print the STL file → Refine the prototype → Material Analysis → Final cup → Support set-up → Parabolic flight → Discussion of the results

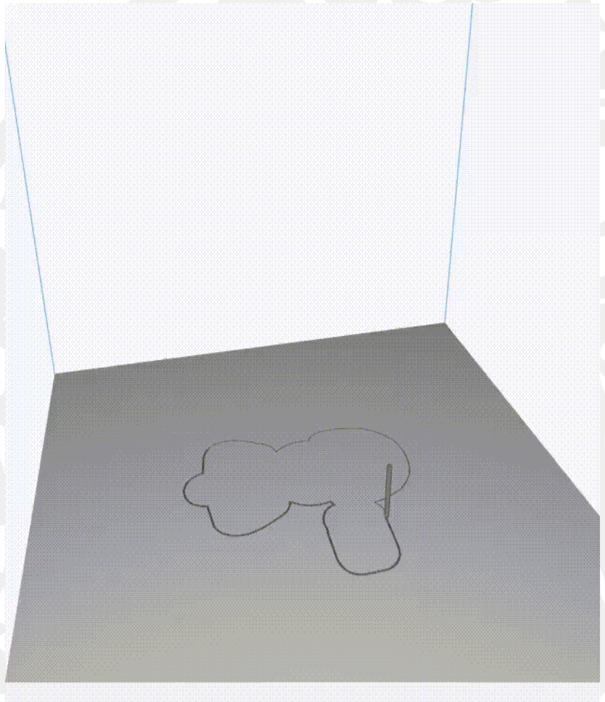
Empiric Simulation – CAD Model

Prototype

- Using Blender, we exported the CAD file in the STL format in order to 3D print it and then we checked the geometry with MeshLab.
- Finally, we sliced the model using Cura to have a preview of the final product.



Different views of the CAD model

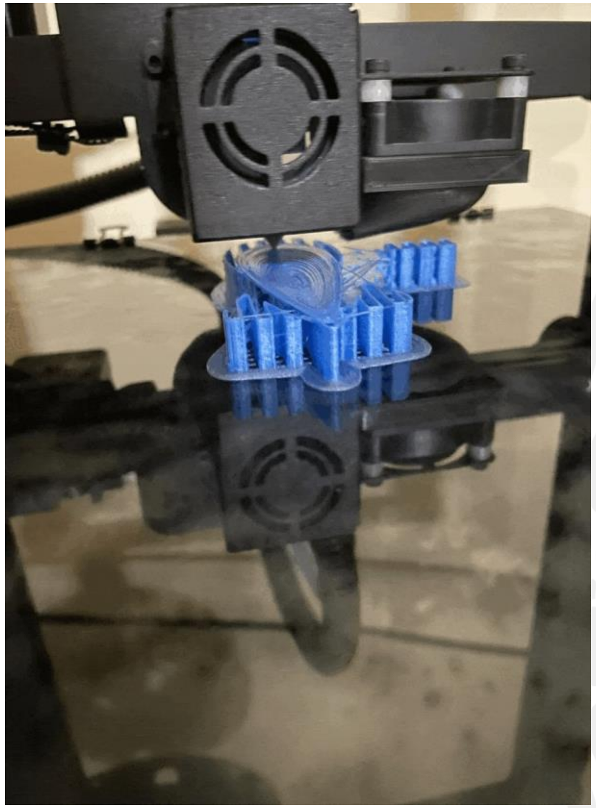


3D printing simulation

Empiric Simulation – 3D Printing

Prototype

- In order to check the quality of the CAD model, we decided to print a prototype using PLA.
- It is now sure that the geometry is watertight and well-designed, and it will be suitable for our purposes.



Printing step-by-step
(Alfawise 30 pro)

Final product

Empiric Simulation – Refine the prototype

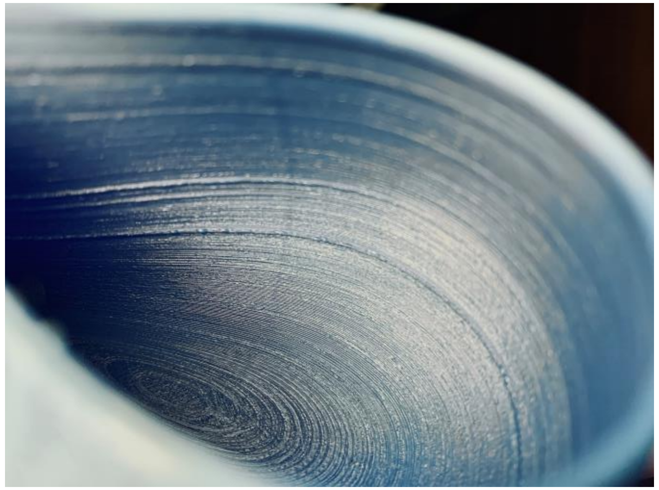
Problems found

1. Clarity	• PLA has low transparency property for thick or complex geometry
2.Anisotropy	• By using FDM printers, the resulting models are characterized by low surface quality
3. Cap	• We need a sealed container in order to not spill the fluid

Empiric Simulation – Refine the prototype

Problems found

Models printed with clear PLA



Detail of the inside of the prototype

Picture of the top of the cup

Empiric Simulation – Refine the prototype

Solutions found

SLA printing

- Resin printed models have a higher surface quality and an almost clear finish

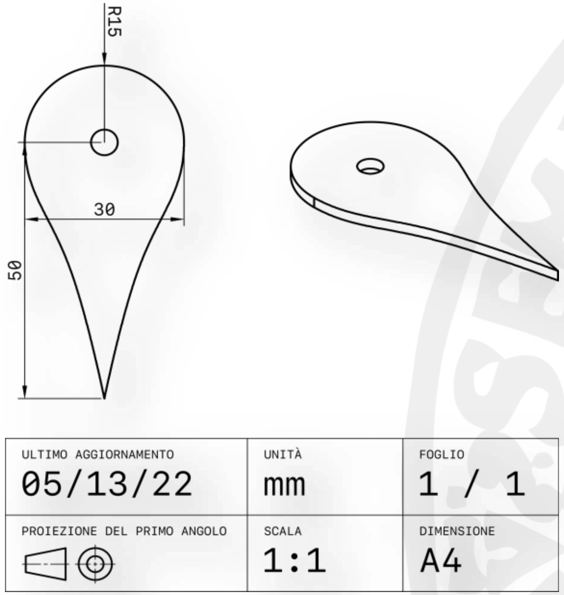
Sealing cap

- A tailormade sealing cap will prevent the spilling of the liquid

Empiric Simulation – Refine the prototype

Solutions found

Resin printed glasses



Final cap design

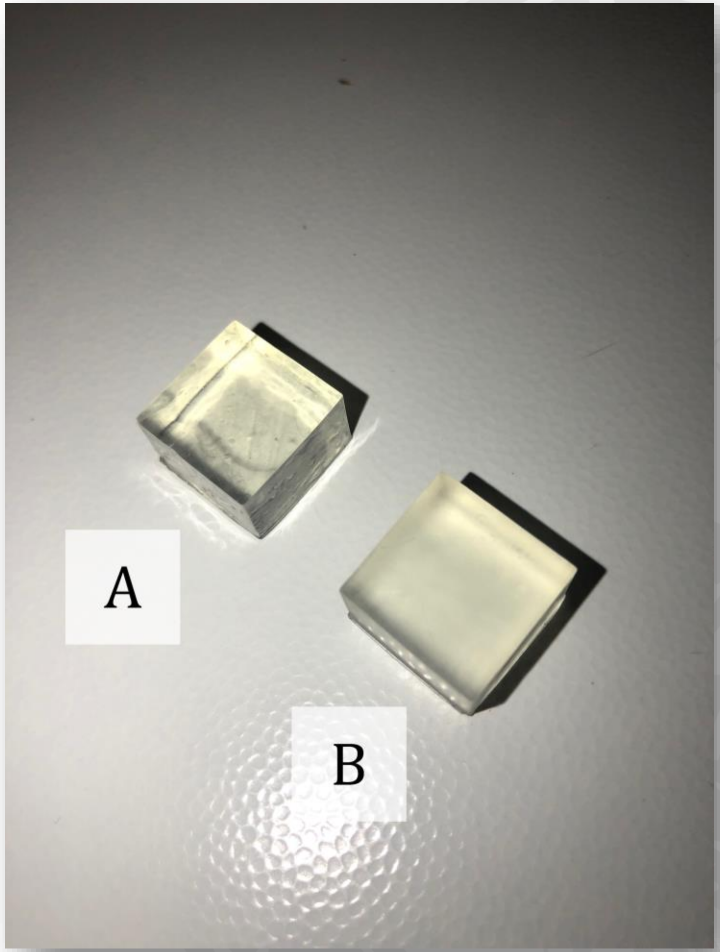
Empiric Simulation – Material Analysis

- We evaluated two different methods of finishing the resin in order to achieve an object that is as transparent as possible but at the same time have a high surface quality. On both samples, we have performed some wettability tests.

Different finishes:

A) Only cured

B) Ethanol + cured

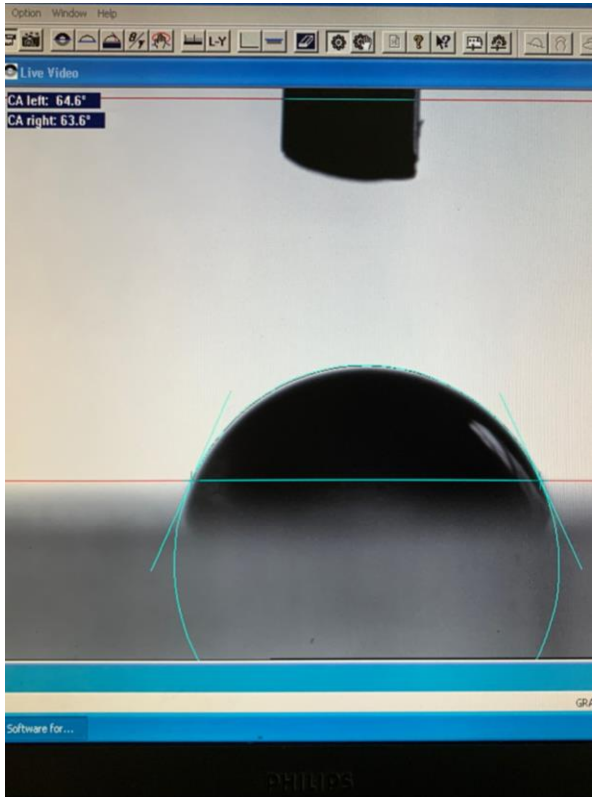


Empiric Simulation – Material Analysis

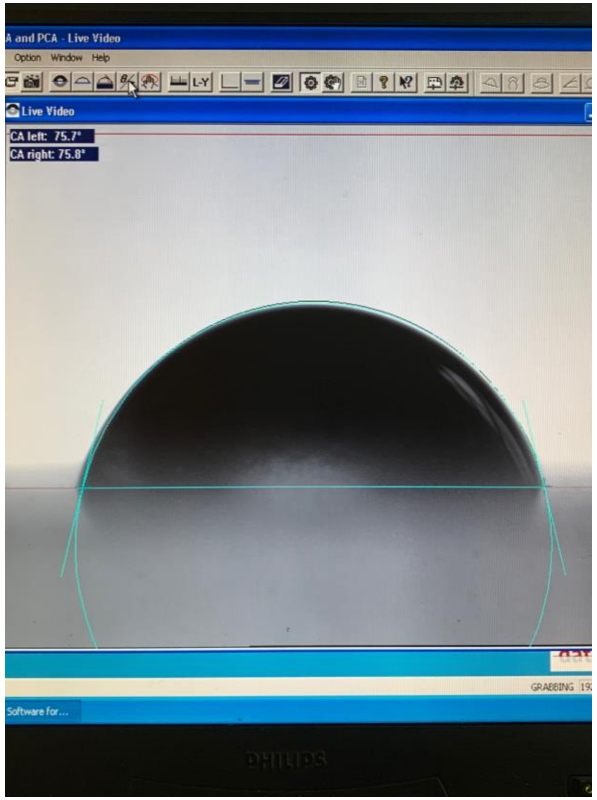
- In order to maximize the capillary action, we need to work on the contact angle [solid + liquid] and the surface tension [liquid]. The cup is printed in resin, so we need to evaluate the best liquid match.

Pure Water	• Distilled water is, among common liquids, one of those with the highest surface tension
Solution of Water and Sodium Chloride	• By adding $NaCl$ to the water, it is possible to improve the surface tension
Vegetable Oil	• In order to also investigate the contribution of contact angle, we chose a liquid that had properties that were different from the water

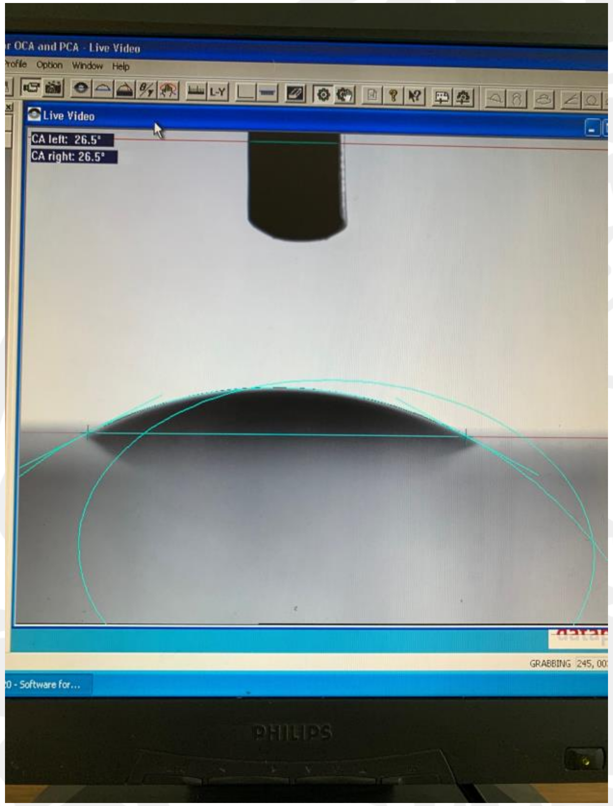
Empiric Simulation – Material Analysis



Water



NaCl + Water [1M]

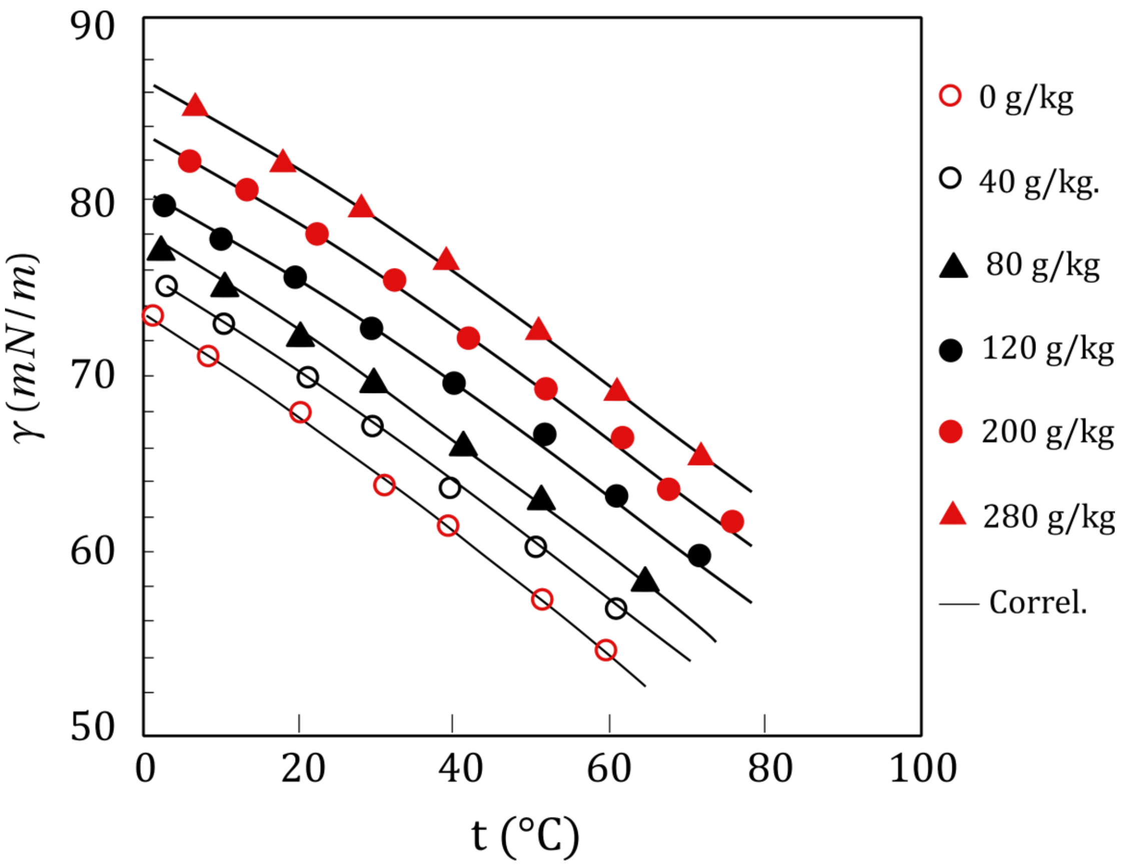


Vegetable Oil

*All the experiments were carried out on the test that has only been cured [A] using the Contact Angle System (Courtesy of Dep. Of Industrial Engineering UniNa).

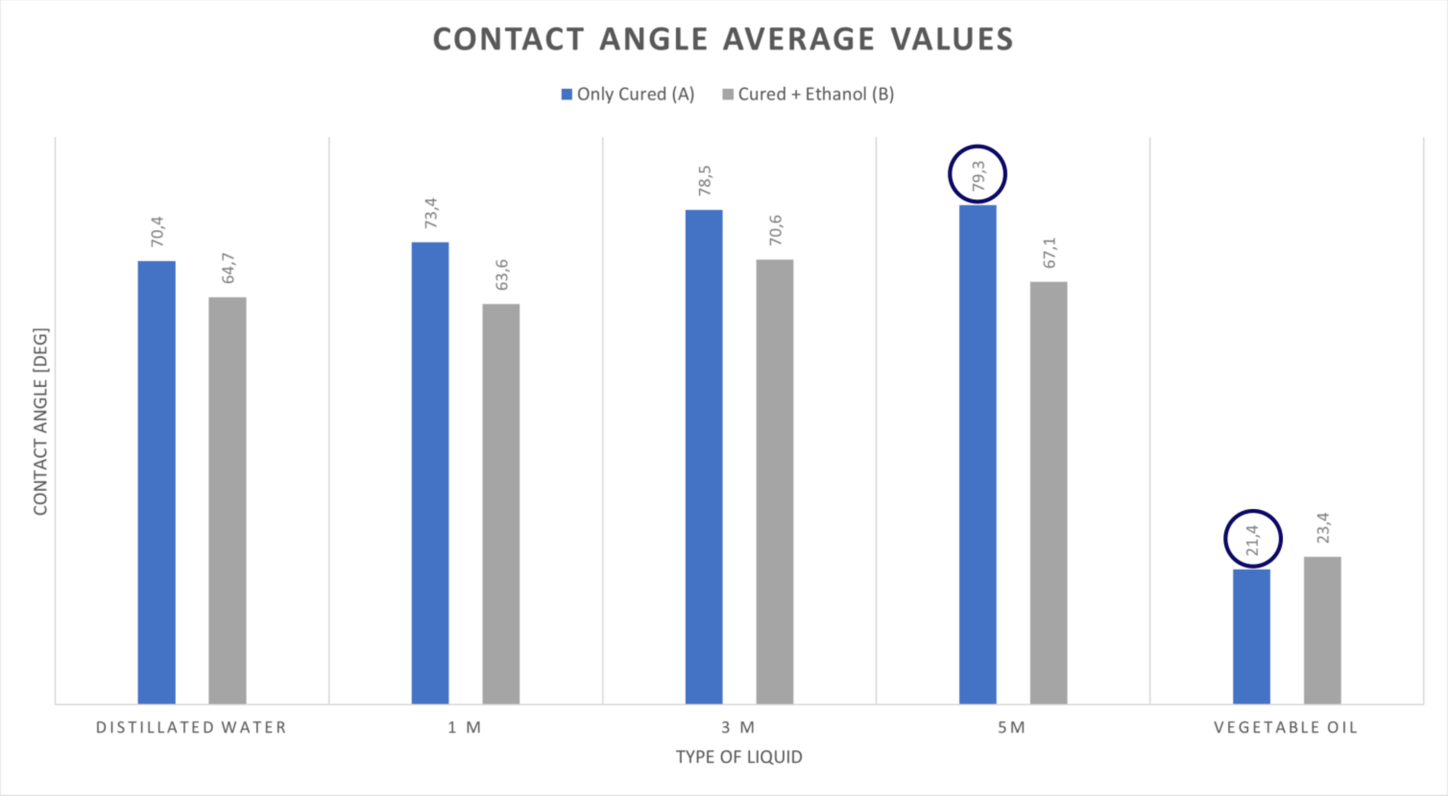
Empiric Simulation – Material Analysis

- As shown in the right picture, it is possible to see that the average surface tension in salted water increase with the salt concentration. So, in our numerical model we have used salted water surface tension that we have evaluated using the right diagram.

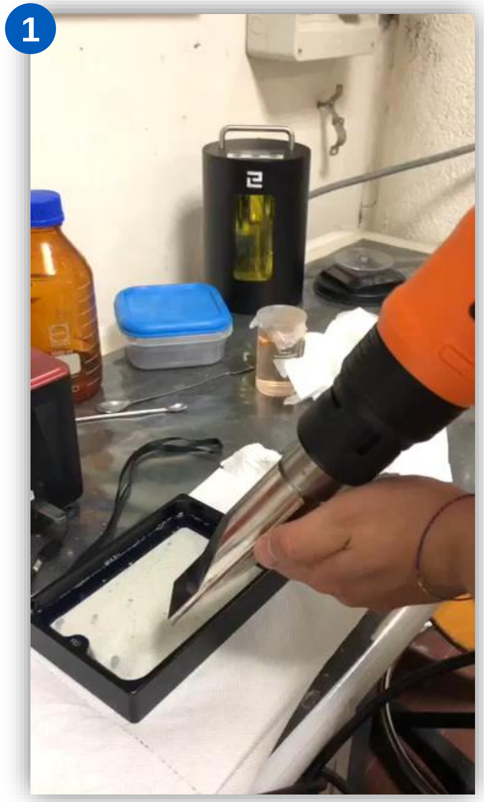


Empiric Simulation – Material Analysis

- Even if water solutions have an average surface tension greater than the oil, after repeating the experiment on both resin samples, we found a higher affinity between the oil and the resin that has being cured and finished with ethanol as the average contact angle is significantly lower than the water solutions' ones. For this reason, in order to highlight the differences, we decided to study the problem in the scenario characterized by the greatest difference of the contact angle.



Empiric Simulation – Final cup

1


Heat Gun

2


Uncured object
(Elegoo Mars Pro 3)

3


Curing Process

4

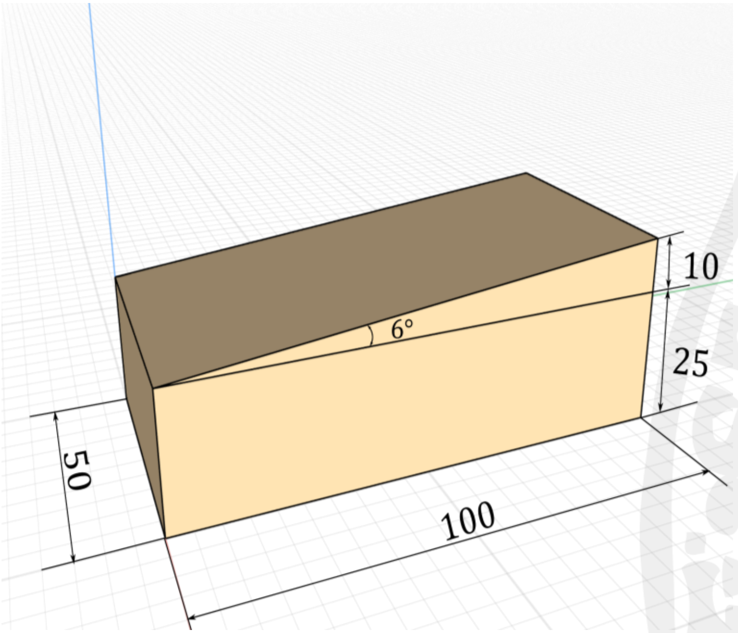

Final product

Courtesy of DIMaCPI labs UniNa

Empiric Simulation – Support set-up

Features:

- Dimensions: We used as references the dimensions of the cup and the platform.
- Tilt: The support is slightly inclined in order to better visualize the phenomenon.
- Material: Wood is easy to shape, and sturdy.

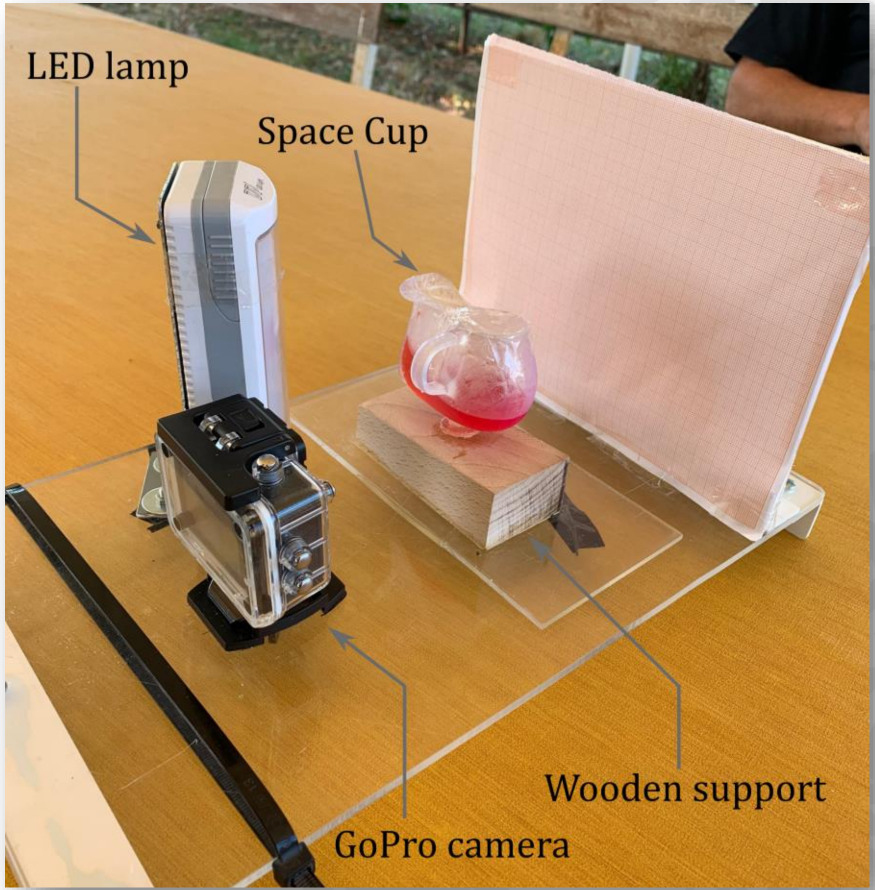


CAD (dimensions in mm)

Render of the wooden support

Empiric Simulation – Support set-up

- The final wooden stand with the cup are placed on the platform using a drilled plexiglass sheet. The camera will record the experiment and the LED lamp will ensure good light through all the experiment. The base will be mounted onboard before the flight.



Final set-up adopted

Empiric Simulation – Parabolic Flight

Operations

Pre-flight

- Filling the cup with the first liquid
- Mount all the elements on the platform

In-flight

- No operation needed

Between-flight

- Make sure the fluid has not been spilled
- Refill the cup with the other liquid

Post-flight

- Collect the clips
- Compare the phenomenon with the one predicted by the numerical simulation

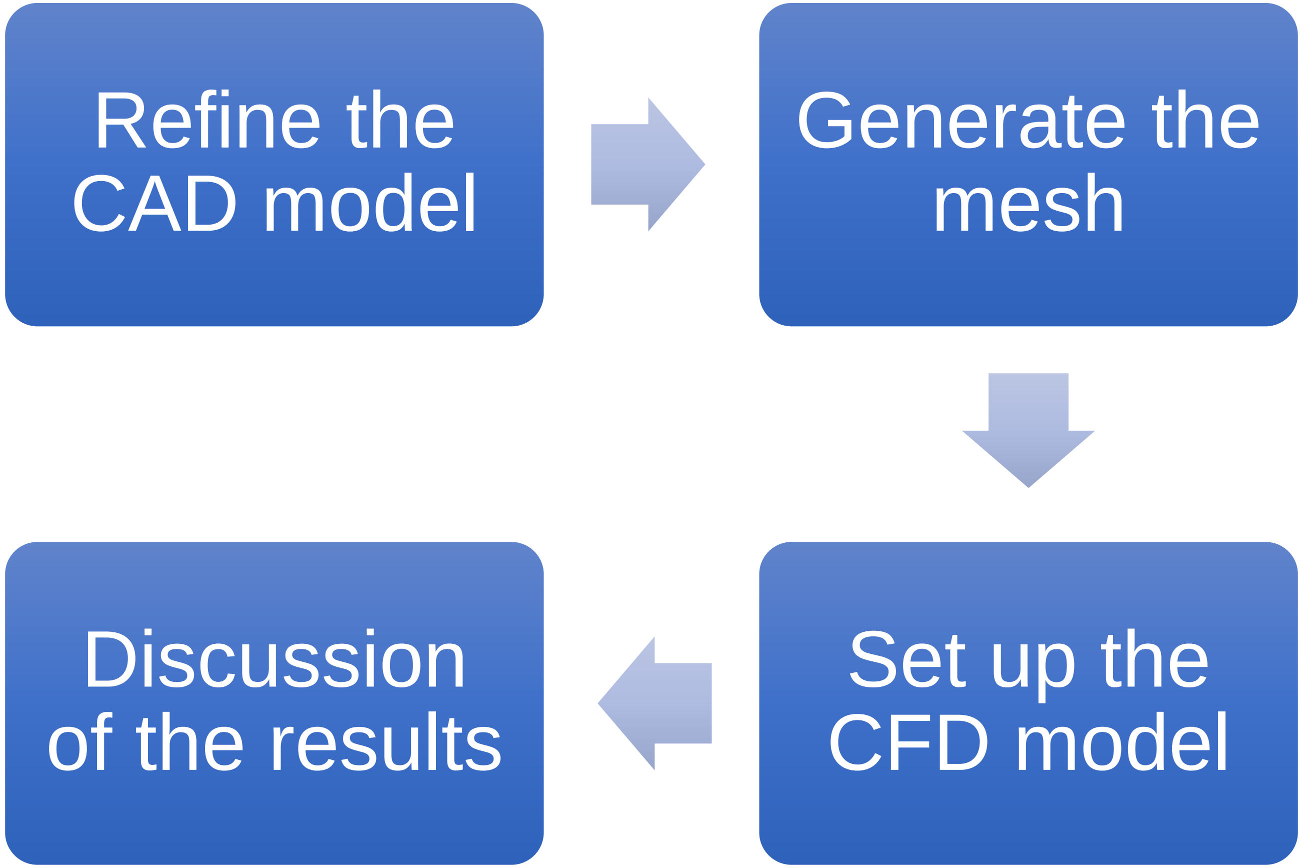
Empiric Simulation – Parabolic Flight

Aircraft and pilot courtesy of A.S. Galassia

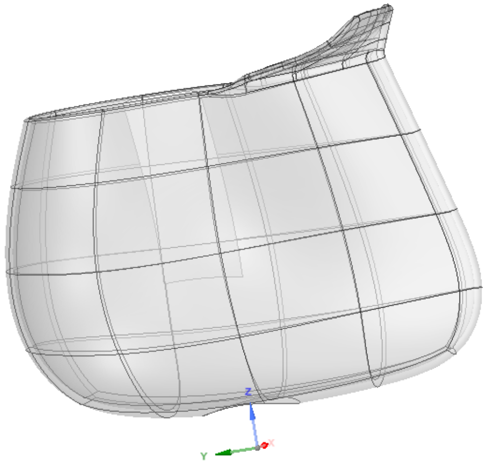
Empiric Simulation – Results

- After analyzing the clips, we can consider one of the first goals we set for ourselves to be completed.
- We have observed that in a microgravity conditions, the water takes almost 2 seconds to arrive to the top of the cup, while the oil takes about 1.5 seconds.

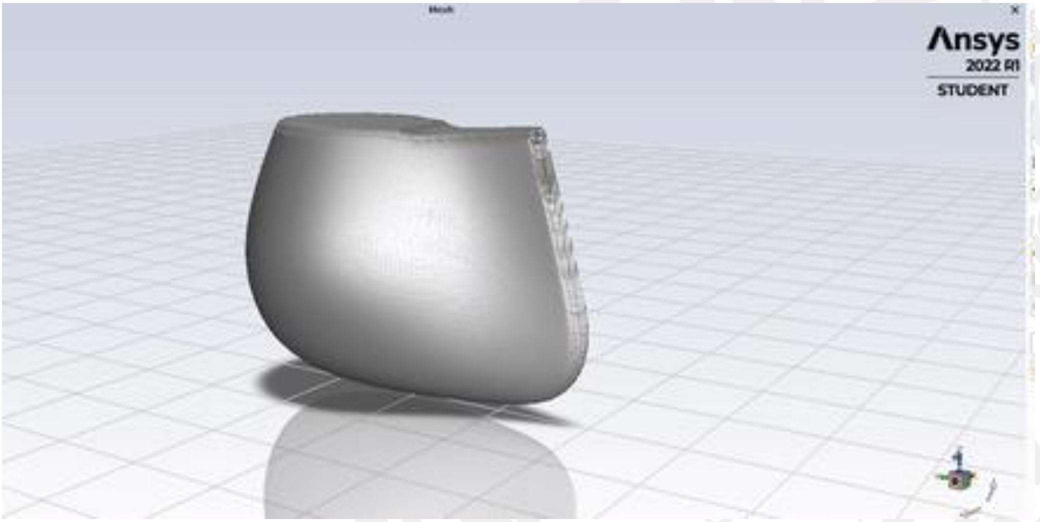
Experimental Sequence – Numerical Simulation



Numerical Simulation – CAD and Mesh



Post-processed IGS file



Resulting mesh

- To optimize the CFD calculation, using SpaceClaim, we decided to remove all the parts not directly linked with the capillary (the handle and the base) and then the mesh was generated using the built-in features of Ansys software (Meshing CFD-PrepPost).

Numerical Simulation – CFD

CFD flowchart

General Model Multiphase
- Materials *
- Boundary Conditions
- Liquid volume definition
- Contact Angle and Surface Tension

Transient 1g condition
- 1g condition to solve the non-physical initial condition

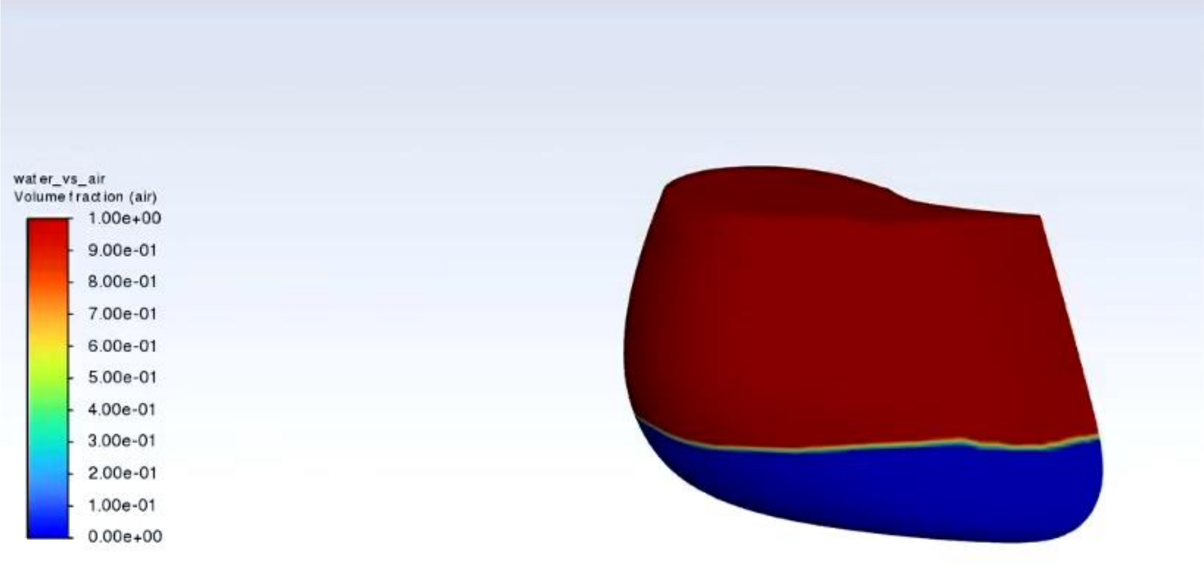
Run Calculation
- Calculation were performed until equilibrium

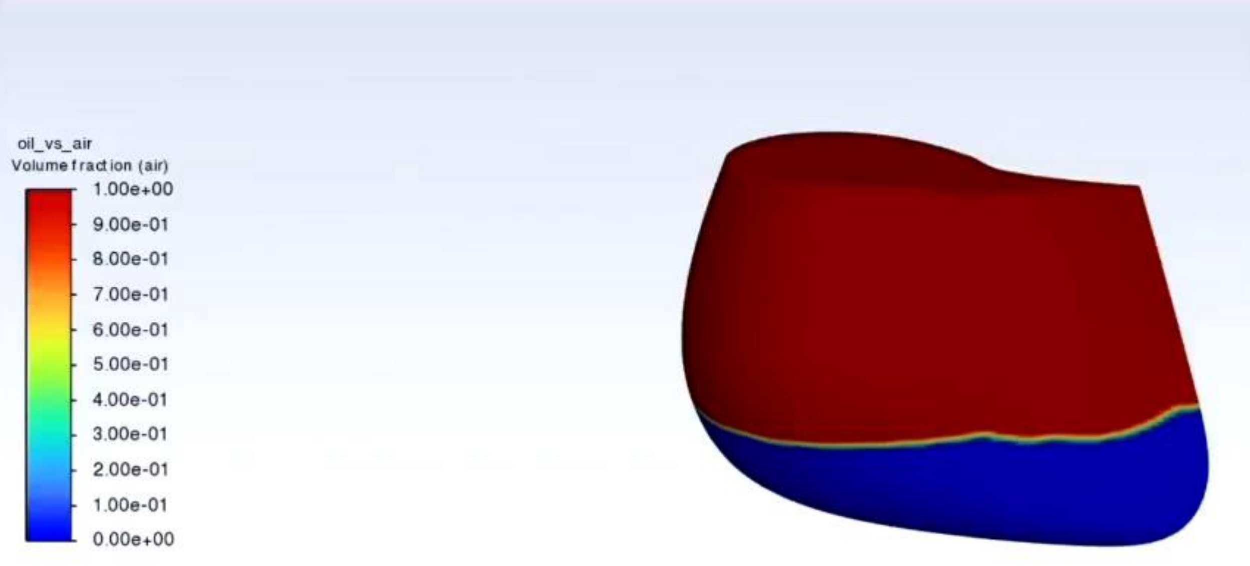
Zero gravity condition
- Remove the gravity from the model

Final Calculation
- Dynamic Contour of the Volume Fraction

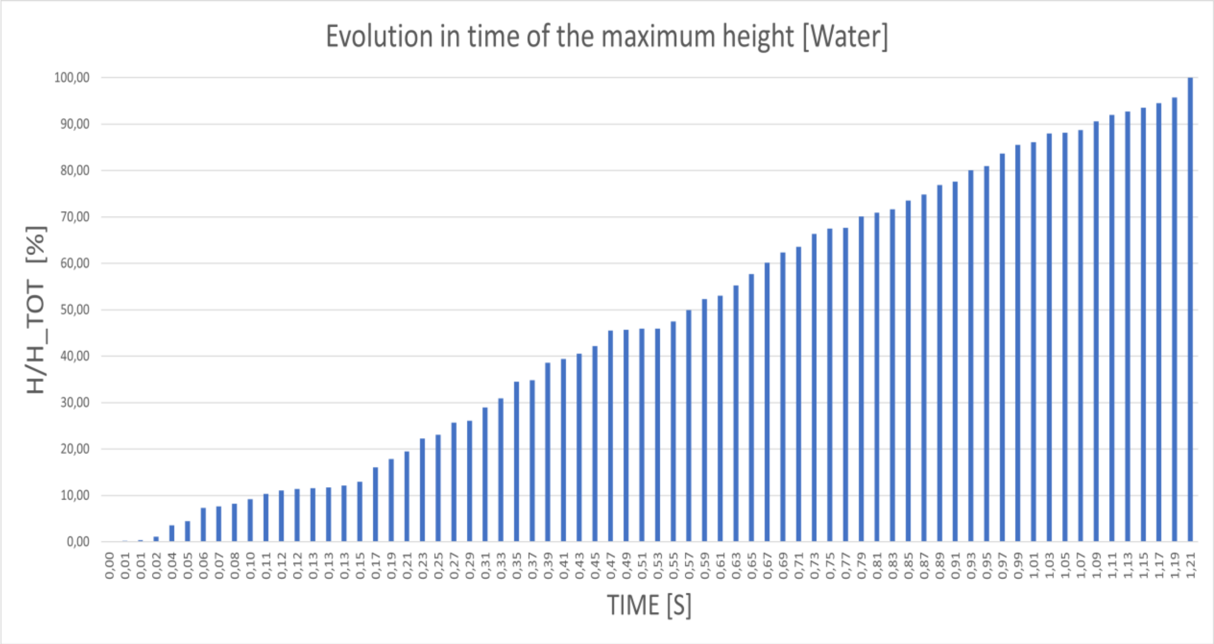
*The same scheme has been used both for the water and the oil Fluent simulation

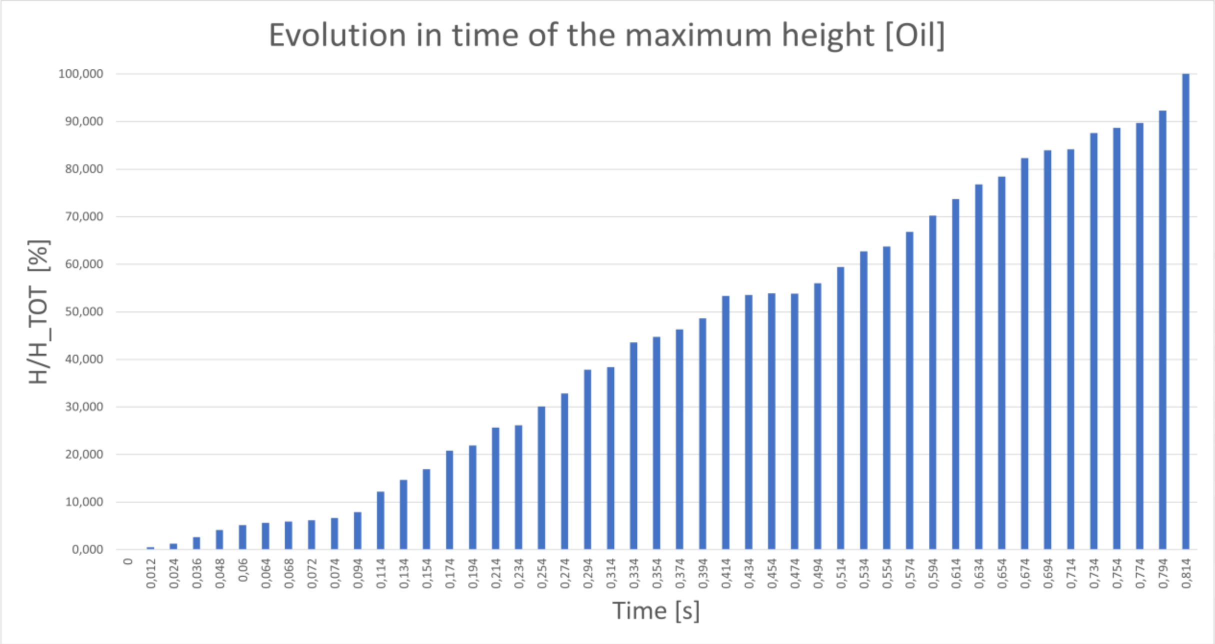
Numerical Simulation – CFD





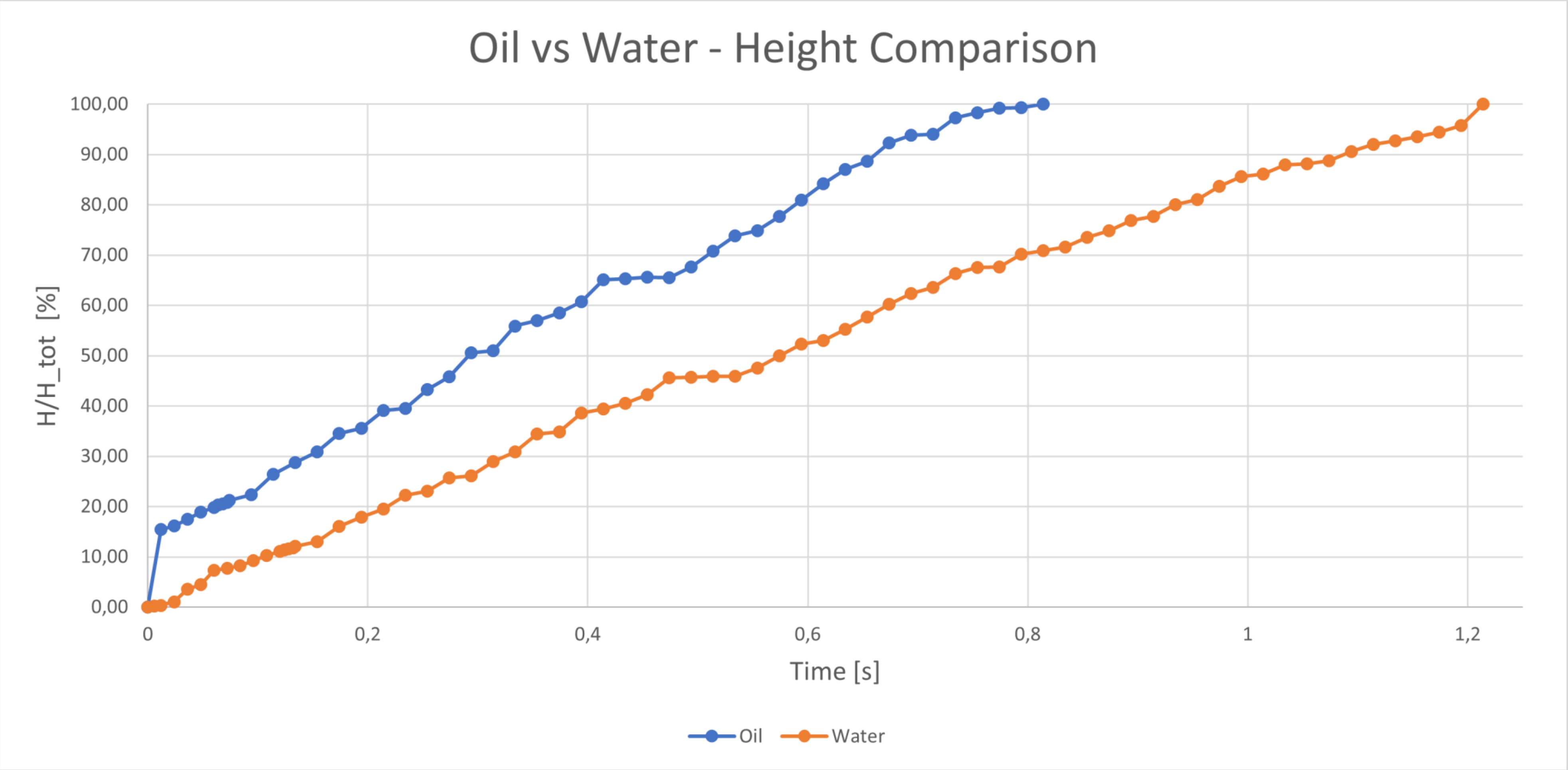
Numerical Simulation – CFD





- The y-axis expresses the percentage of the ratio between the local water column height and the maximum possible one.
- On the x-axis there is the time.

Numerical Simulation – CFD



- The graph was normalized using the highest point of the water column at t=0

Numerical Simulation – Results

- After observing the contour animation and the previous diagrams, the following conclusions can be drawn:
  - After a maximum of 1.2 s, both the liquids have arrived at the highest possible point
  - Although the higher surface tension of the water, due to the influence of the lower contact angle and, so, of the higher wettability, the oil raise is faster than the water one

Deliverables

- After evaluating the empirical and numerical experiments, it is possible to state that:
  - The previous numerical simulations were carried out in 0-g condition, so in the reduced gravity condition achieved onboard of the parabolic flight, in both cases, the raise has been slower
  - The geometry of the cup enhances the phenomenon of capillarity, allowing good rise results even in non-ideal zero-gravity conditions
  - Our analyses showed that the material chosen to make the cup and the liquid are the elements that most affect the timing and capillary rise for the same geometry

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THANK YOU
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