MULTI-PHYSICS MODELING OF 3D BIOPRINTING OF PCL SCAFFOLDS FOR IN-SPACE ADDITIVE MANUFACTURING

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College Park, MD

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2020 – 2024

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Research Interests:

- Computational Mechanics
- In-Space FDM modeling
- Multi-scale and Multi-physics modeling techniques

Research Projects: 2020-2023

- Microgravity modeling for polymers extrusion 3D printing.
- Multi-phase materials modeling for composites 3D printing.
- Multi-physics process modeling for metals 3D printing.
- Residual Stress and thermal distortion modeling.

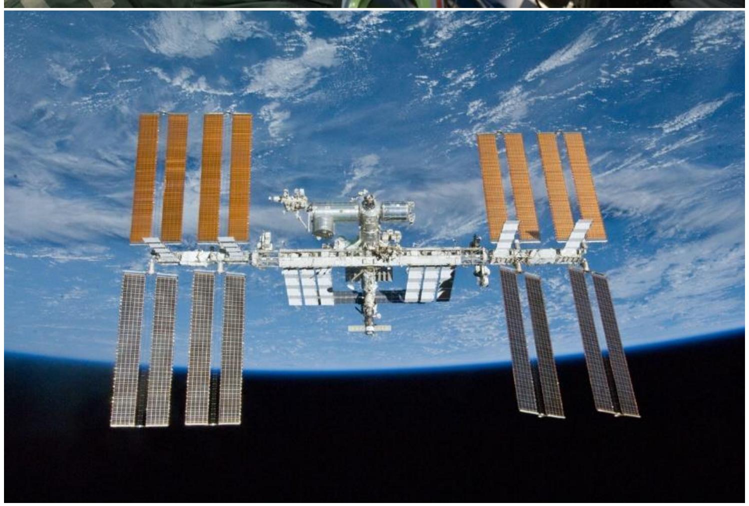
PROBLEM MOTIVATION

ADDITIVE MANUFACTURING

https://arch-medical.com/capabilities/additive-manufacturing.html

https://www.meticuly.com/meticuly-published-in-additive-manufacturing-magazine/

https://www.ge.com/additive/industry/medical/orthopedics



The **I**nternational **S**pace **S**tation has continuously been home to astronauts for long-duration space scientific research and study.

This logistics support system works well for a spacecraft that is orbiting 250 miles above Earth. However, it is not practical to supply anything needed like the Earth.

Astronauts on these long voyages need to be able to make their own spare parts, tools, and materials essentially on demand – both for routine needs and to adapt quickly to unforeseen ones.

In-Space 3D printing technology could be an ANSWER.

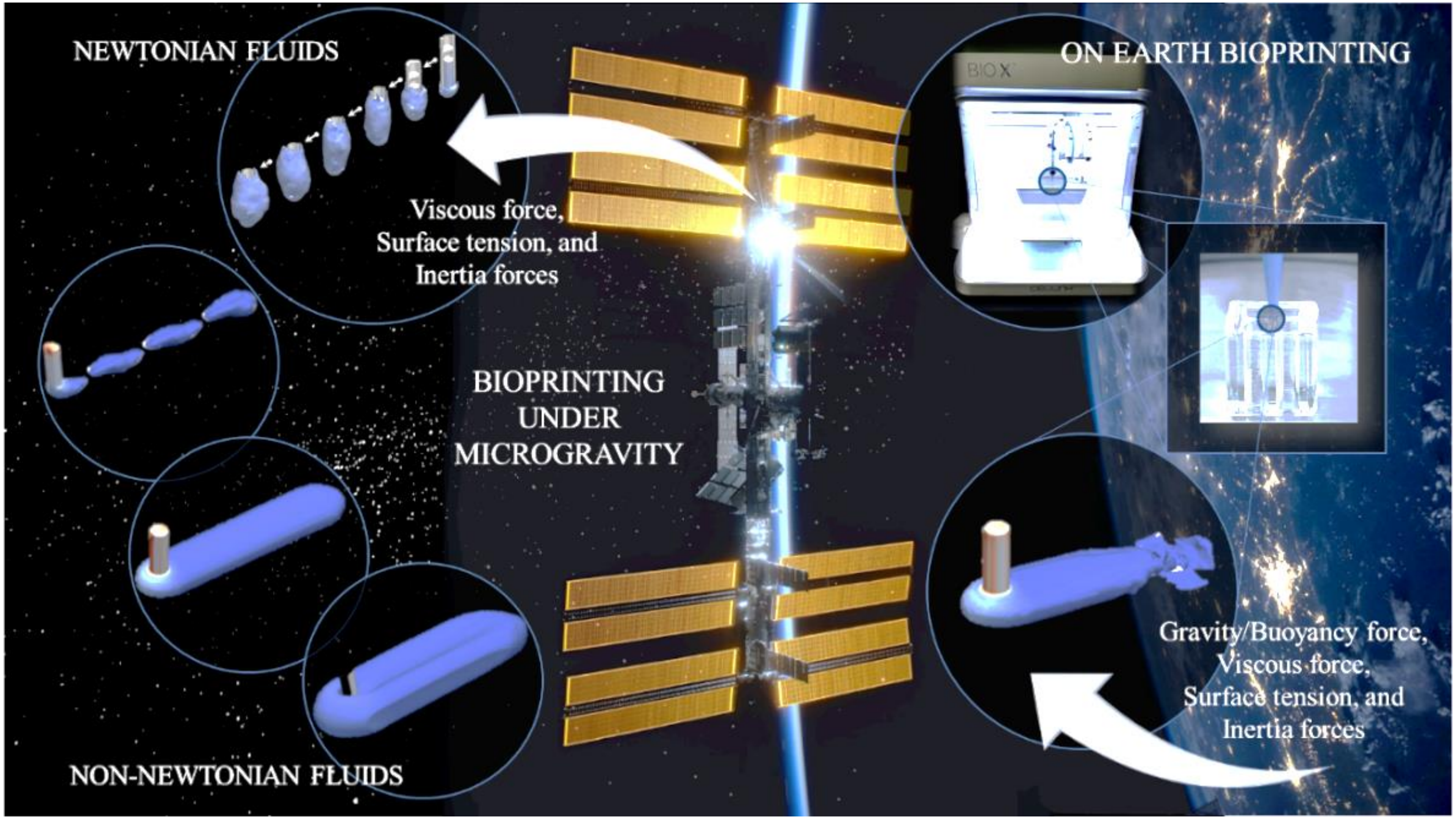
FUSED DEPOSITION MODELING

is being acquired with good application in the International Space Station.

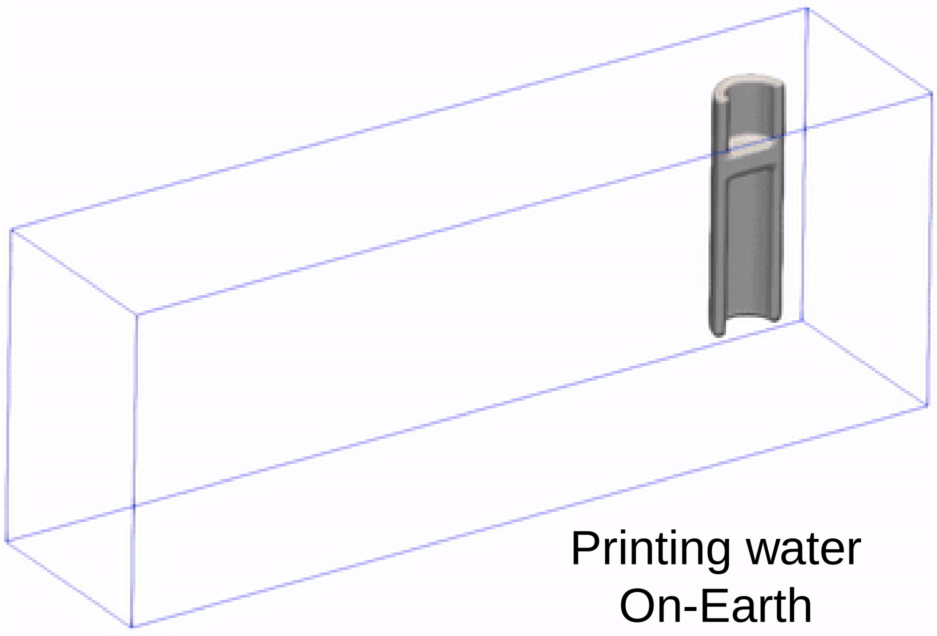
IN-SPACE ADDITIVE MANUFACTURING

https://www.nasa.gov/mission_pages/station/research/news/3d-printing-in-space-long-duration-spaceflight-applications

PROBLEM **M**OTIVATION



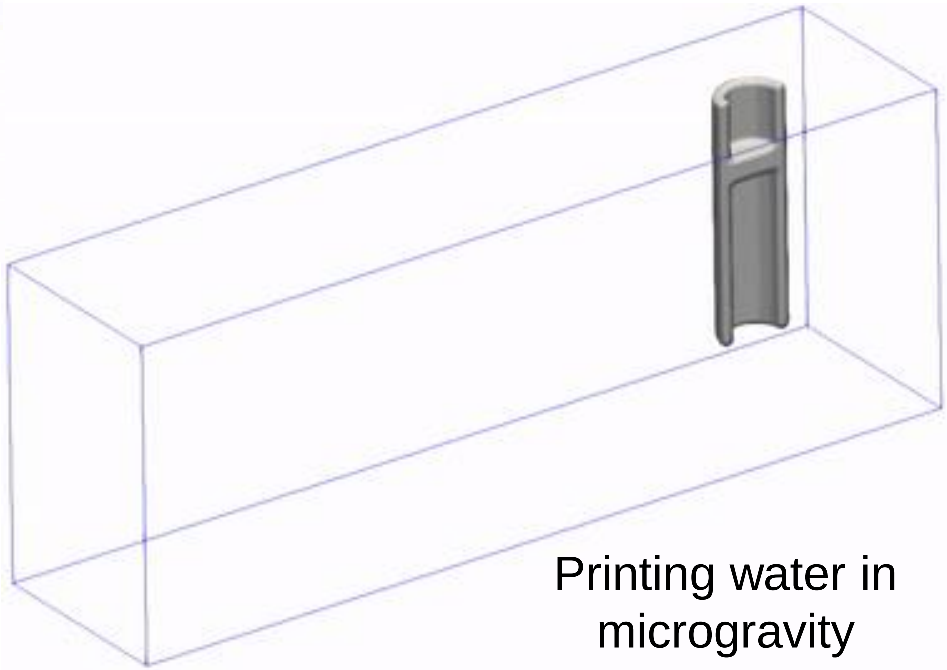
IN-**S**PACE **A**DDITIVE **M**ANUFACTURING



Printing water On-Earth

Newtonian Fluid : Water

On-Earth v/s Microgravity



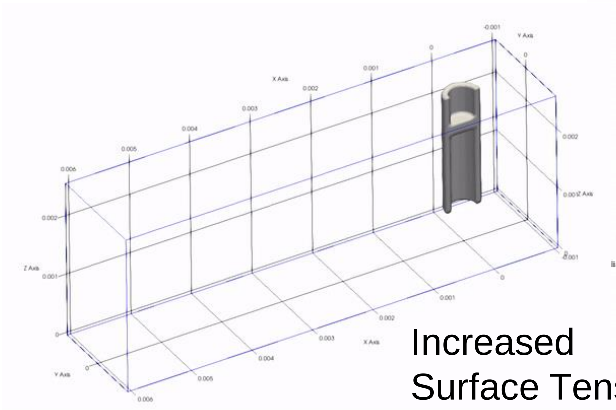
Printing water in microgravity

3D printing parameters:

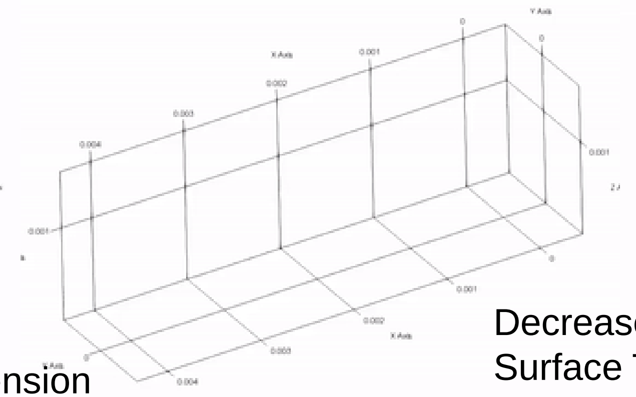
- Pressure ~25 kPa
- Speed 1200 $\mathrm{mm/min}$
- Time 0.1 seconds

NEWTONIAN in MICROGRAVITY

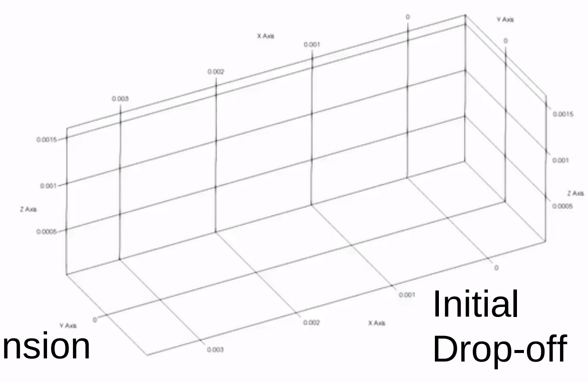
Non-Newtonian Fluid On-Earth v/s Microgravity



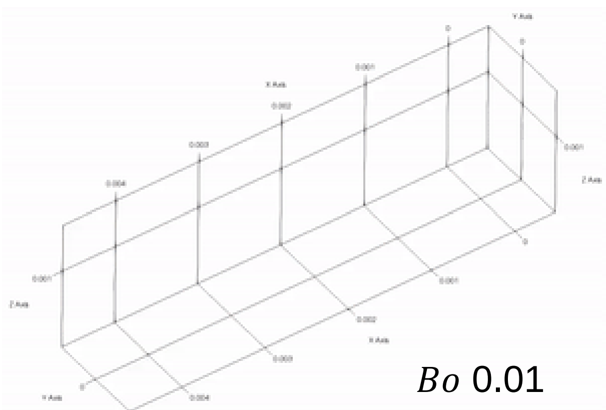
Increased
Surface Tension



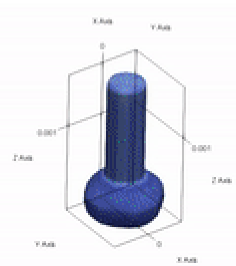
Decreased
Surface Tension



Initial
Drop-off



Bo 0.01
Fr 0.5
We 0.0127



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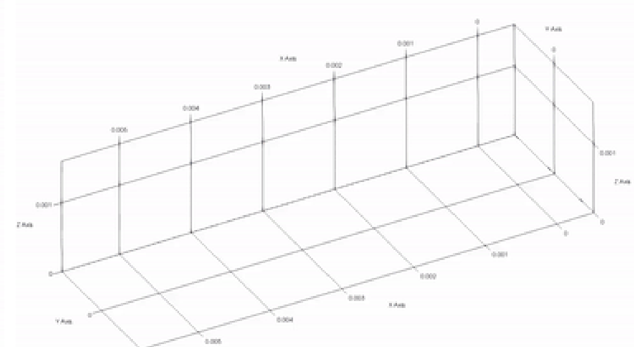
Fr 0.5
We 1.813



Bo 0.01
Fr 10
We 0.246

NON-**N**EWTONIAN in **M**ICROGRAVITY

3DPrinting parameters: **Pressure** 25 kPa
Speed 1200 $\mathrm{mm/min}$ | **Time** 0.1s

How do we model the **microgravity Fused Deposition Modeling** process?

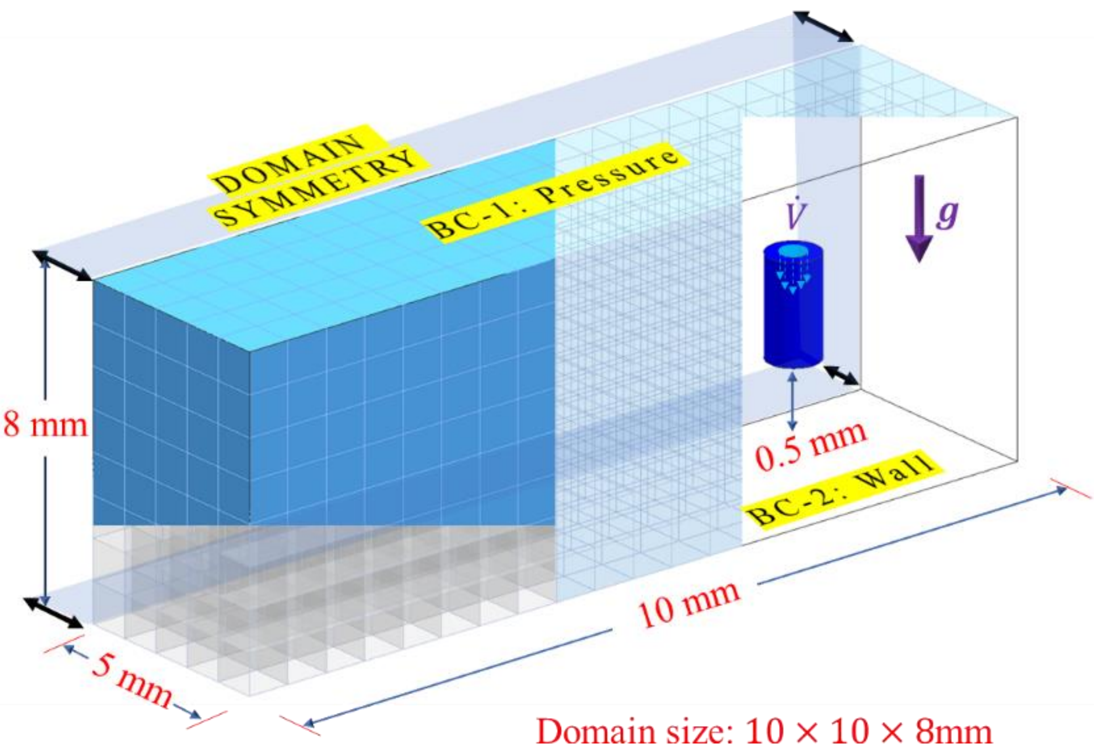
What happens if we print **Poly-Caprolactone (PCL)** powders using the FDM process?

What happens to the **fluid flow** during the printing of PCL non-Newtonian fluids under **microgravity**?

What happens to the **heat transfer** during the printing of PCL non-Newtonian fluids under **microgravity**?

Computational Fluid Dynamics + Volume Of Fluid

CFD-VOF method domain



$$\frac{\partial F}{\partial t} + \nabla \cdot (\boldsymbol{v}\ F) = 0$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\,\boldsymbol{v} = -\frac{1}{\rho}\ \nabla p + \mu \nabla^2 \boldsymbol{v} + \boldsymbol{g} + \boldsymbol{f}$$

$$\rho \frac{D\boldsymbol{u}}{Dt} = -\nabla p + \rho \boldsymbol{g} + \sigma k \nabla \gamma + \mu \nabla^2 \boldsymbol{u}$$

$$(\nabla \cdot \boldsymbol{v}) = 0$$

$$\frac{\partial h}{\partial t} + (\boldsymbol{v} \cdot \nabla) h = -\frac{1}{\rho}\ \nabla \cdot k \nabla T + \dot{q}$$

$$q_{loss} = C_l (T - T_l) + L_v$$

$$M_{net} = R_{accom} * \sqrt{\frac{M}{2\pi R T_{bdy}}} * (P_l^{sat} - P_v)$$

time-dependent fluid fraction step function F

$\boldsymbol{f}$ is the force source representing surface tension force and the Marangoni force at the meltpool zone

C_l is the specific heat of the fluid,

T_l is the solidus temperature, and

L_v is the latent heat of evaporation.

R_{accom} is the accommodation constant,

M is the molecular weight of the vapor,

P_v is the vaporization pressure and

P_l^{sat} is the saturation pressure

σ is the surface tension,

κ is the curvature,

$\boldsymbol{n}$ is the surface normal vector,

ρ is the volume-averaged density,

$\boldsymbol{g}$ is the acceleration due to gravity,

μ represents the viscosity,

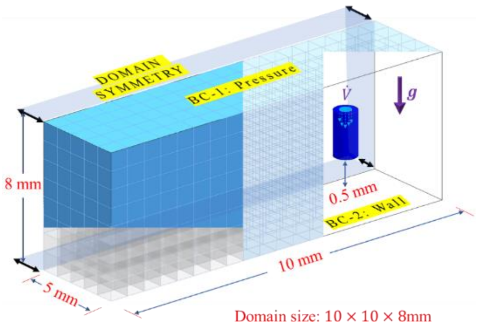
h is the enthalpy,

k is the thermal conductivity, and

T is the temperature.

CFD-VOF MODELING METHOD

Computational Fluid Dynamics + Volume Of Fluid



$$\rho \frac{D\boldsymbol{u}}{Dt} = -\nabla p + \rho \boldsymbol{g} + \sigma k \nabla \gamma + \mu \nabla^2 \boldsymbol{u}$$

$$Bo = \frac{\rho \boldsymbol{g} d^2}{\sigma}$$ Bond number

$$Fr = \frac{\boldsymbol{u}}{\sqrt{\boldsymbol{g} d}}$$ Froude number

$$We = \frac{\rho \boldsymbol{u}^2 d}{\sigma}$$ Weber number

$$Pe = \frac{\rho\, c_p\, \boldsymbol{v}_{max}\, r_s}{k}$$ Peclet number

$$Ma = -\frac{d\sigma}{dT} \frac{L_s \Delta T}{\mu \alpha}$$ Marangoni number

$$\mu = m(\dot{\gamma})^{n-1}$$ Power Law

The gravity in the model was changed from 9.81m/s^2 to 0.12m/s^2.

The solidus temperature was set at 60C, and the latent heat of fusion was set at 6000kJ/Kg.

These two variables were increased by 10% in the microgravity conditions with a hypothesis that the solidification temperature increases with a decrease in gravity.

The thermal properties were kept constant instead of temperature-dependent to study the effect of surface tension, inertia force, viscous force, and gravity forces.

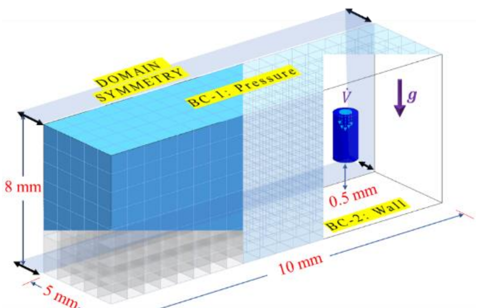
The effect of surface tension was kept constant for both microgravity and on-earth printing conditions.

The reason for this was to use the Bond number as a reference to distinguish between microgravity and on-earth printing.

The $\boldsymbol{Bo}$ for on-earth printing was **6.3** based on the nozzle diameter of 400μm, and it is **0.07** for microgravity conditions.

MICROGRAVITY MODELING

Computational Fluid Dynamics + Volume Of Fluid



Domain size: 10 × 10 × 8mm

$$\rho \frac{D\boldsymbol{u}}{Dt} = -\nabla p + \rho \boldsymbol{g} + \sigma k \nabla \gamma + \mu \nabla^2 \boldsymbol{u}$$

$Bo = \frac{\rho \boldsymbol{g} d^2}{\sigma}$ Bond number

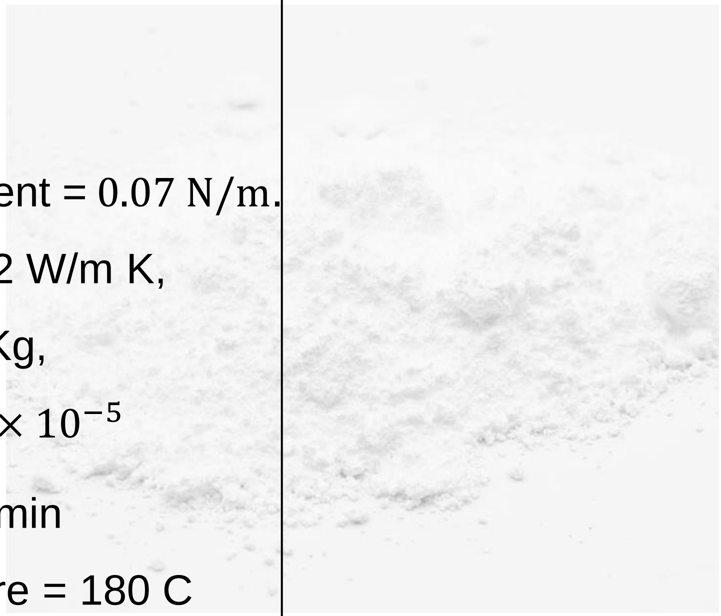
$Fr = \frac{\boldsymbol{u}}{\sqrt{\boldsymbol{g} d}}$ Froude number

$We = \frac{\rho \boldsymbol{u}^2 d}{\sigma}$ Weber number

$Pe = \frac{\rho\, c_p\, \boldsymbol{v}_{max}\, r_s}{k}$ Peclet number

$Ma = -\frac{d\sigma}{dT} \frac{L_s \Delta T}{\mu \alpha}$ Marangoni number

$\mu = m(\dot{\gamma})^{n-1}$ Power Law



Viscosity= $24.53\ \mathrm{Pa \cdot s}$

$\mathrm{n} = 0.1$

Density = $1124\ \mathrm{kg/m^3}$

Surface tension coefficient = $0.07\ \mathrm{N/m}$.

Thermal conductivity = 2 W/m K,

Specific heat = 2000 J/Kg,

Thermal expansion = 5×10^{-5}

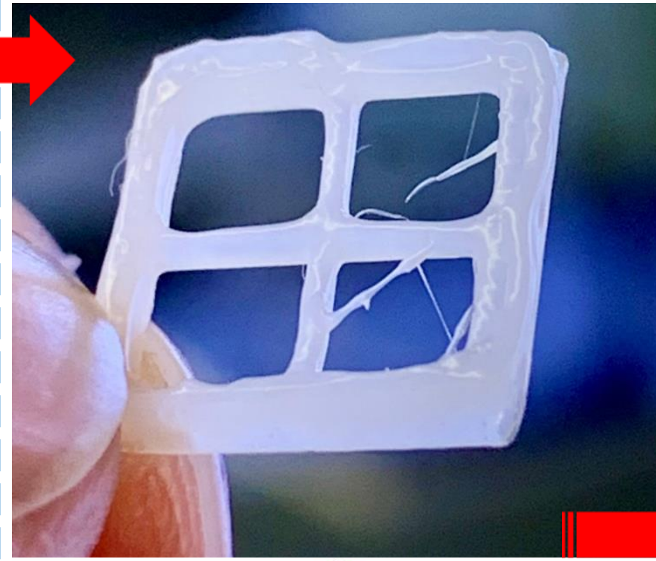
Printing speed = 3 mm/min

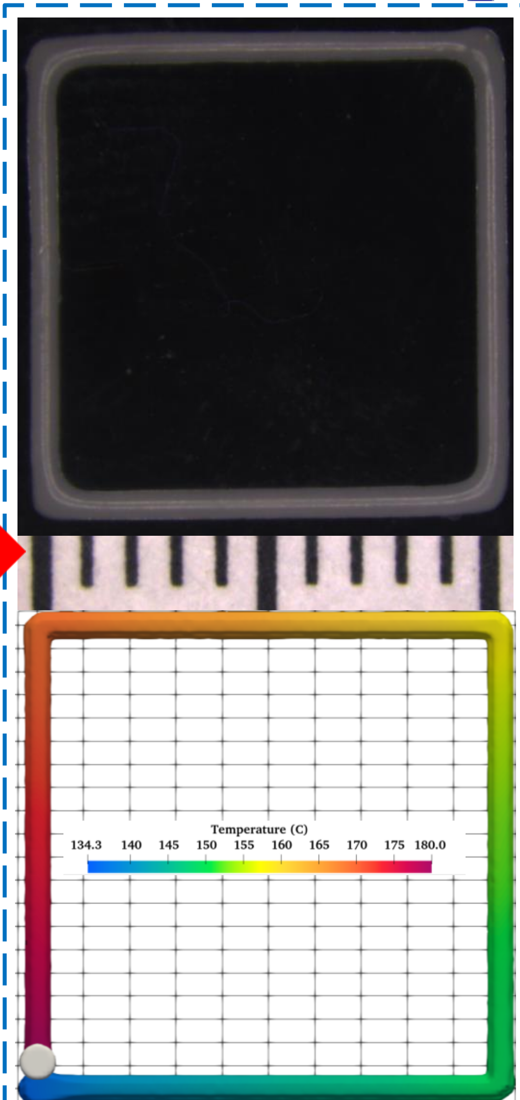
PCL heating temperature = 180 C

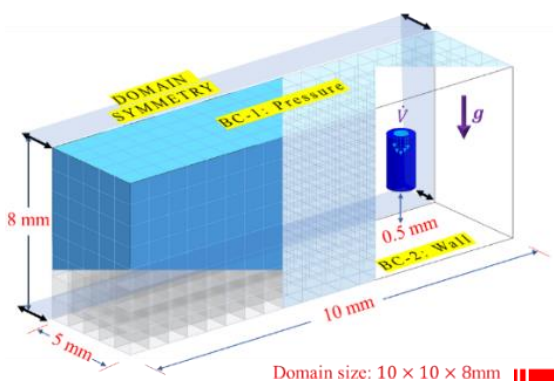
The printing environment = 20.15 C

PCL MATERIAL

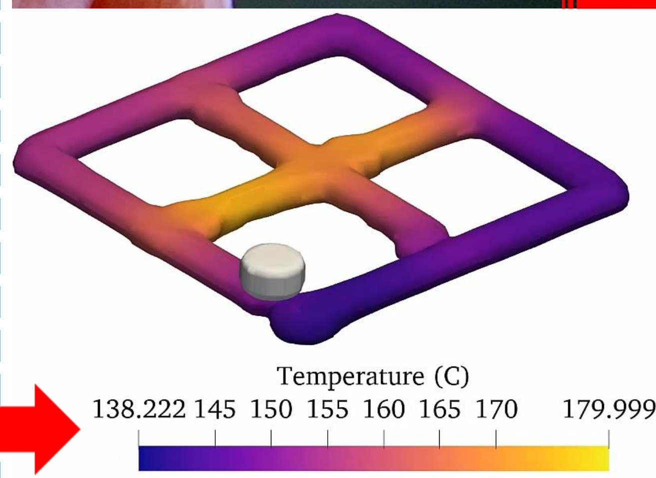
Bio-X Bio Printer





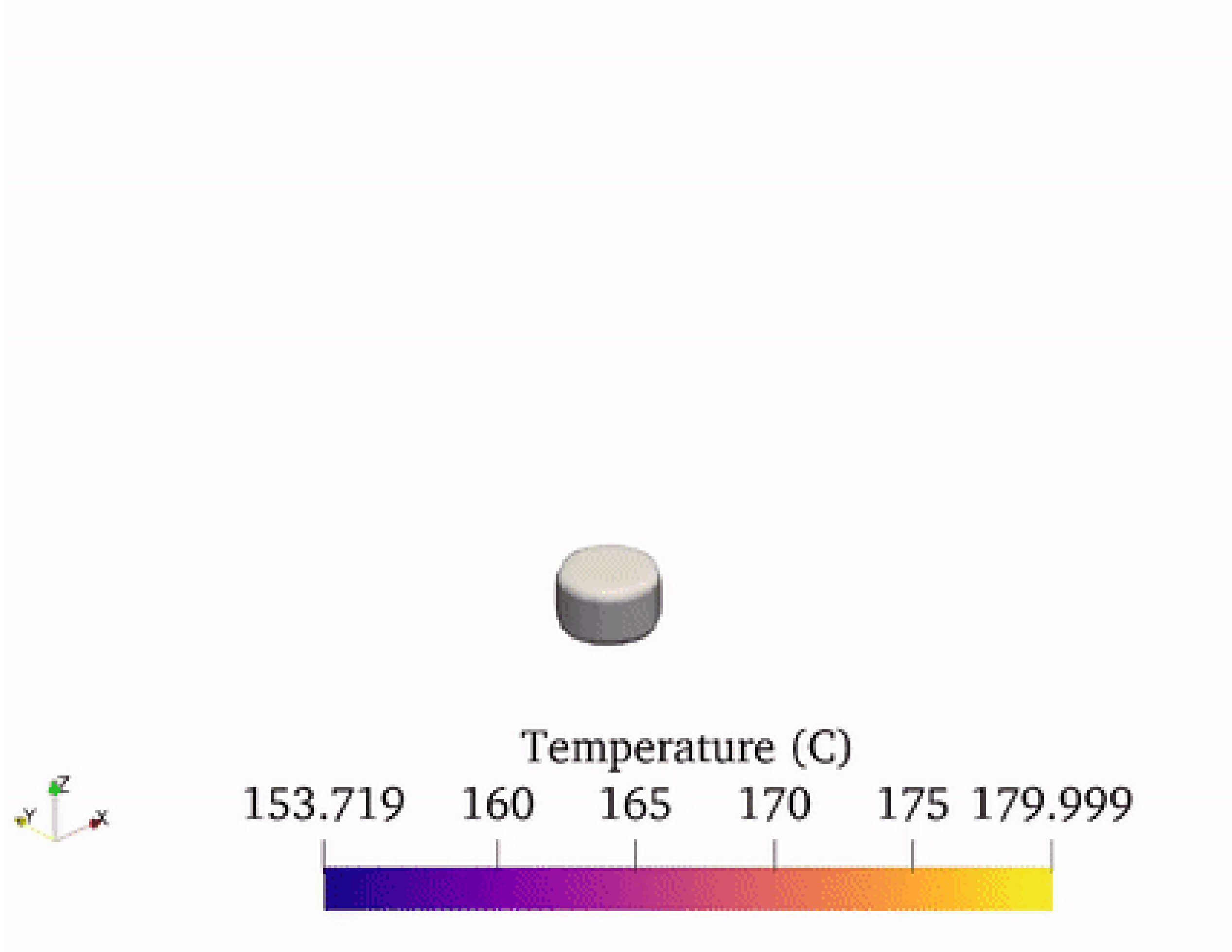


CFD-VOF



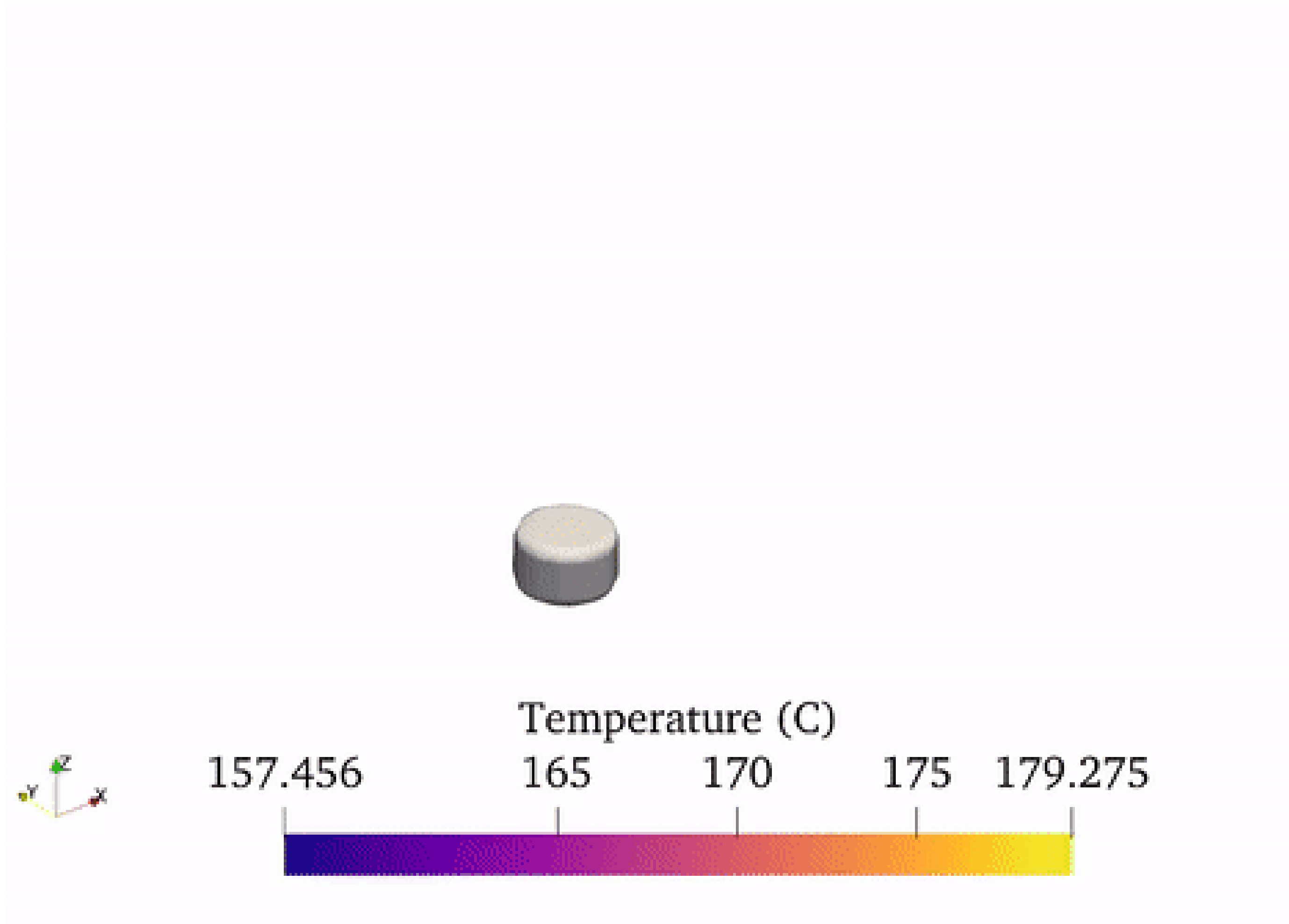
ON-EARTH MODELING VALIDATION

PCL multi-layer grid structure 3D Bio Printing On-Earth



ON-**E**ARTH **PCL** MULTI-LAYER **P**RINTING

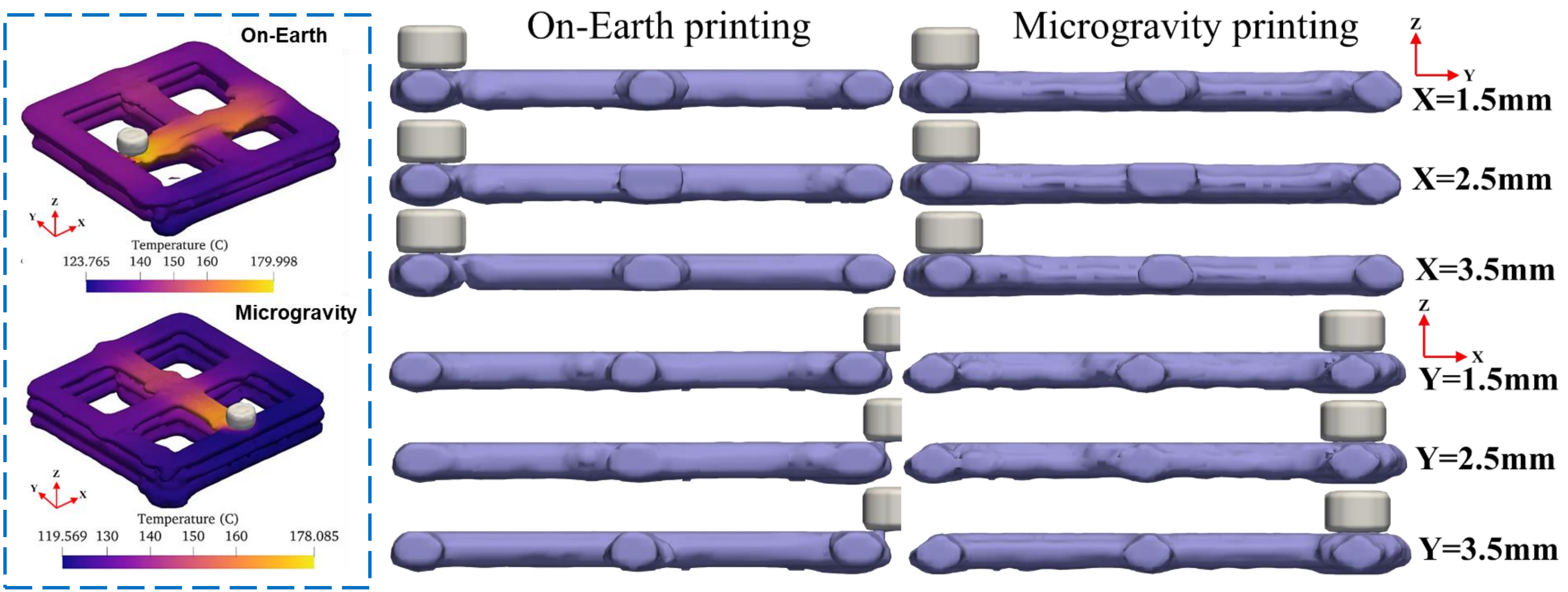
PCL multi-layer grid structure 3D Bio Printing under Microgravity



MICROGRAVITY **PCL** MULTI-LAYER **P**RINTING

On-Earth v/s Microgravity

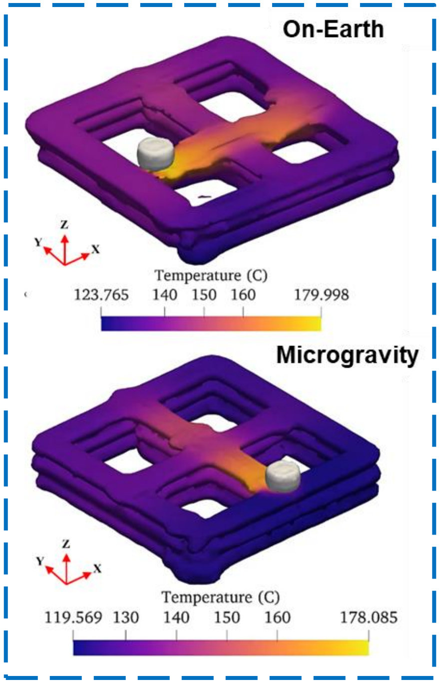
AFTER FIRST-LAYER PCL PRINTING

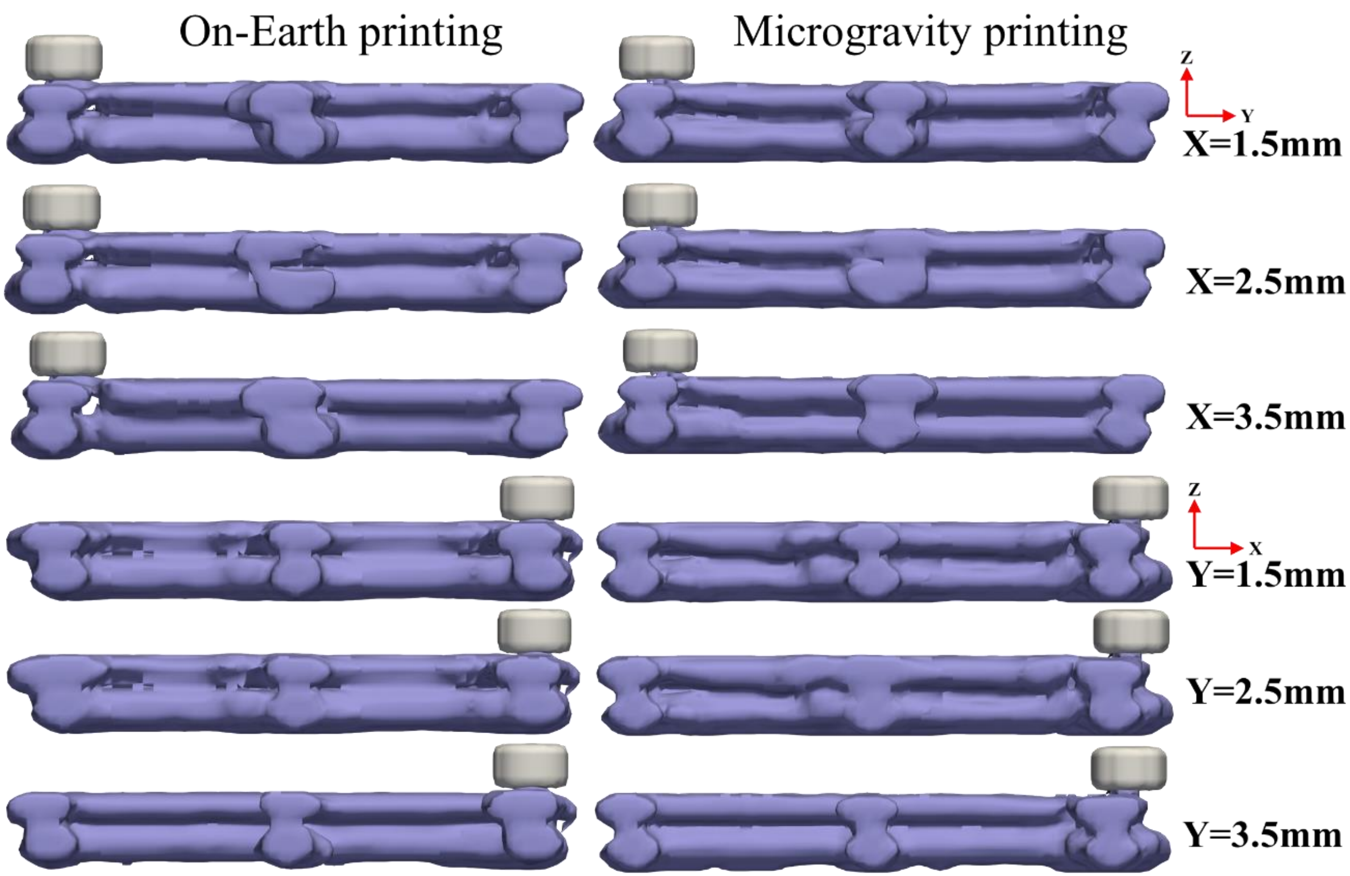


ON-EARTH V/S MICROGRAVITY

On-Earth v/s Microgravity

AFTER SECOND-LAYER PCL PRINTING

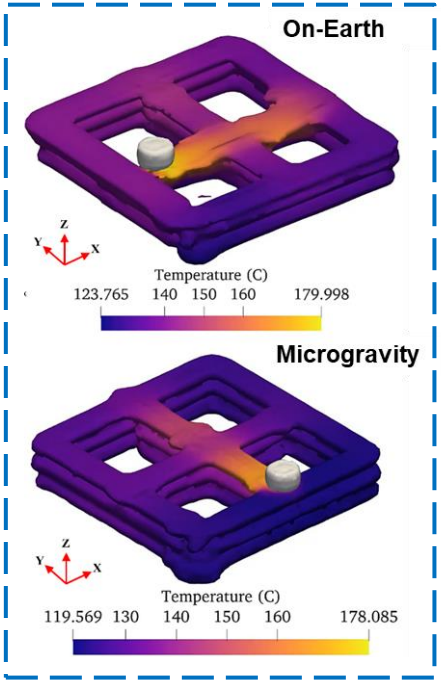


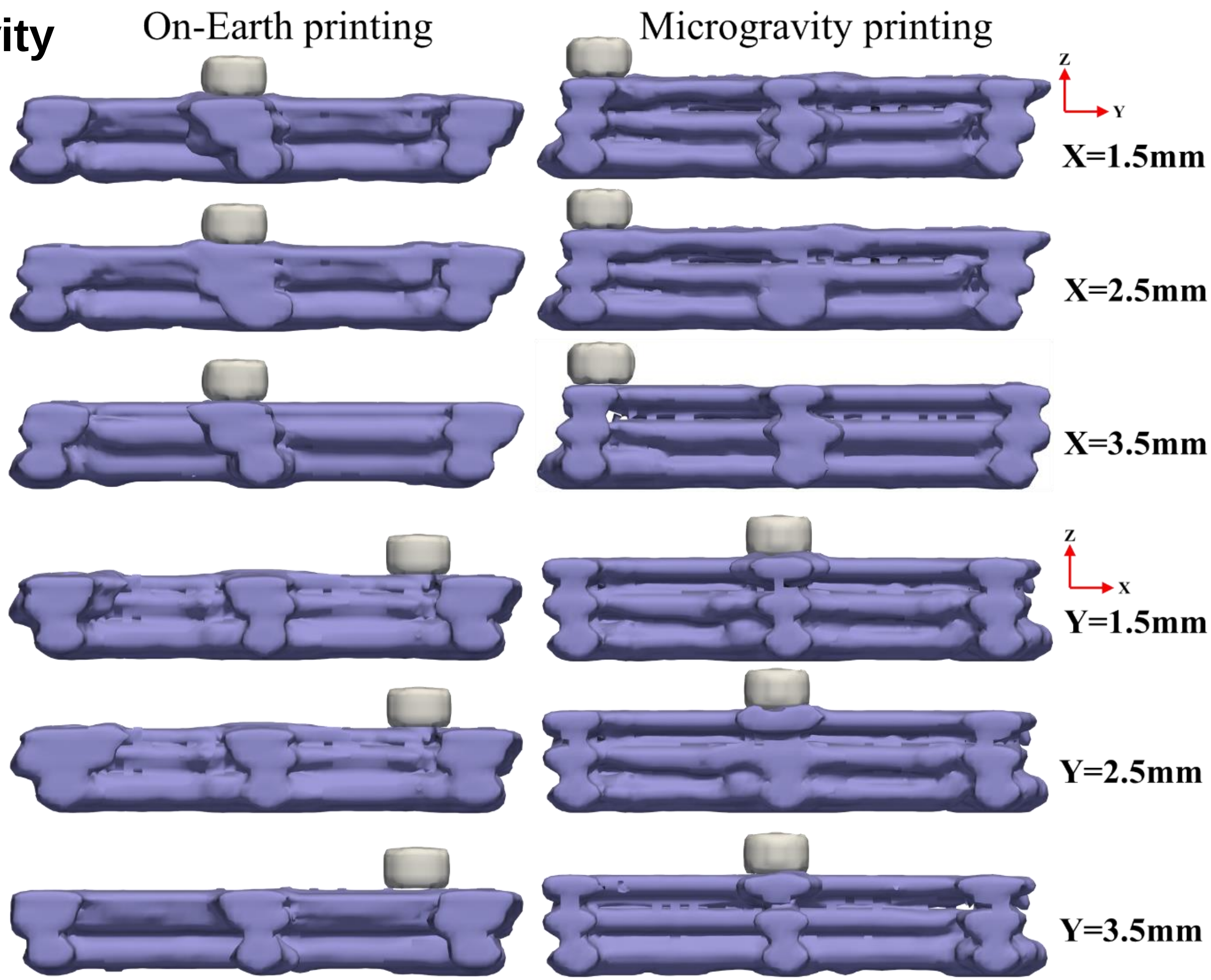


ON-**E**ARTH V/S **M**ICROGRAVITY

On-Earth v/s Microgravity

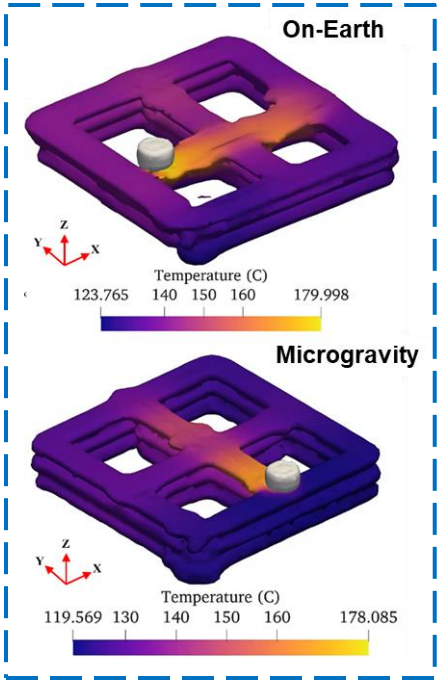
AFTER THIRD-LAYER PCL PRINTING

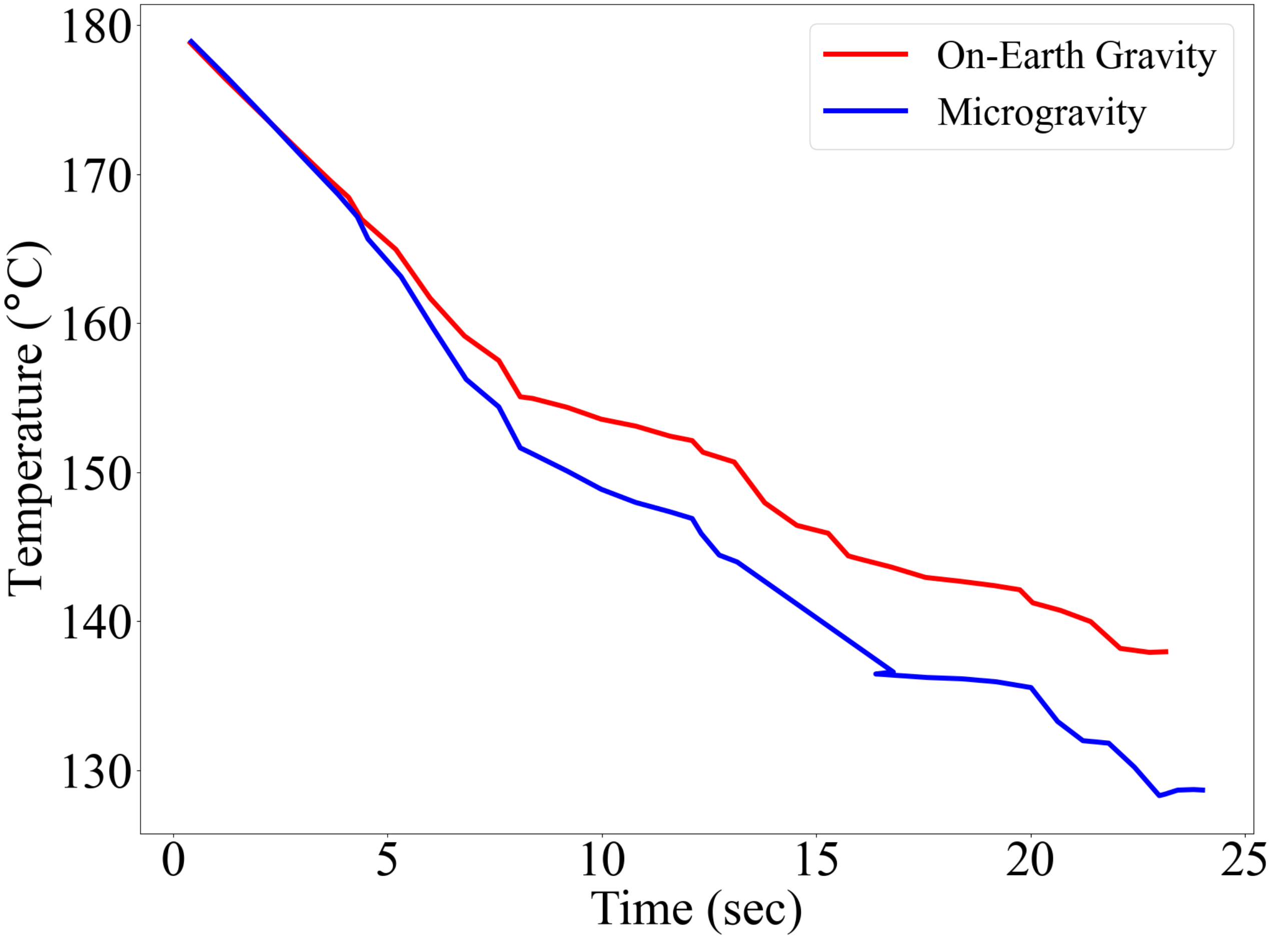




ON-EARTH V/S MICROGRAVITY

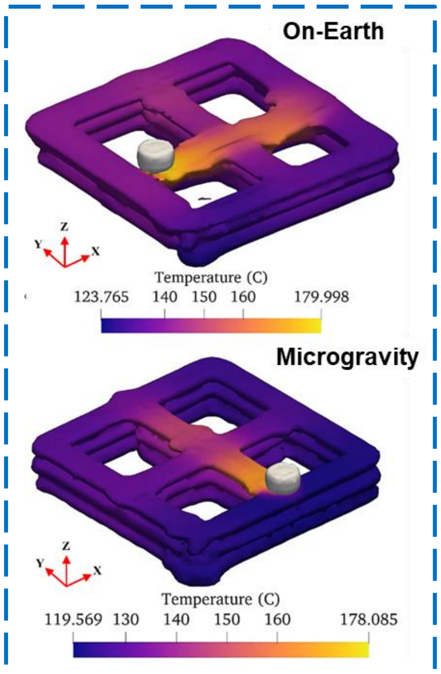
On-Earth v/s Microgravity PCL Printing

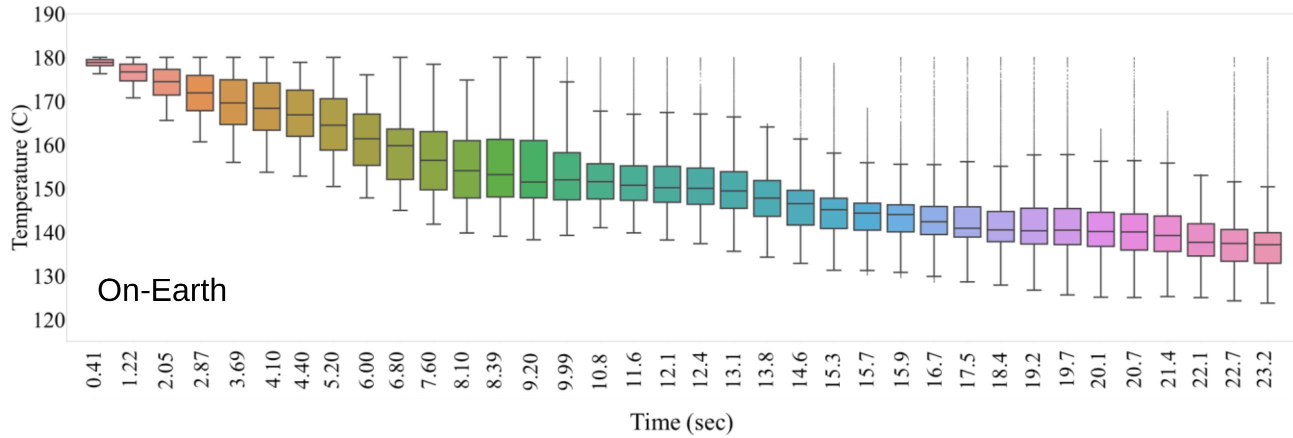


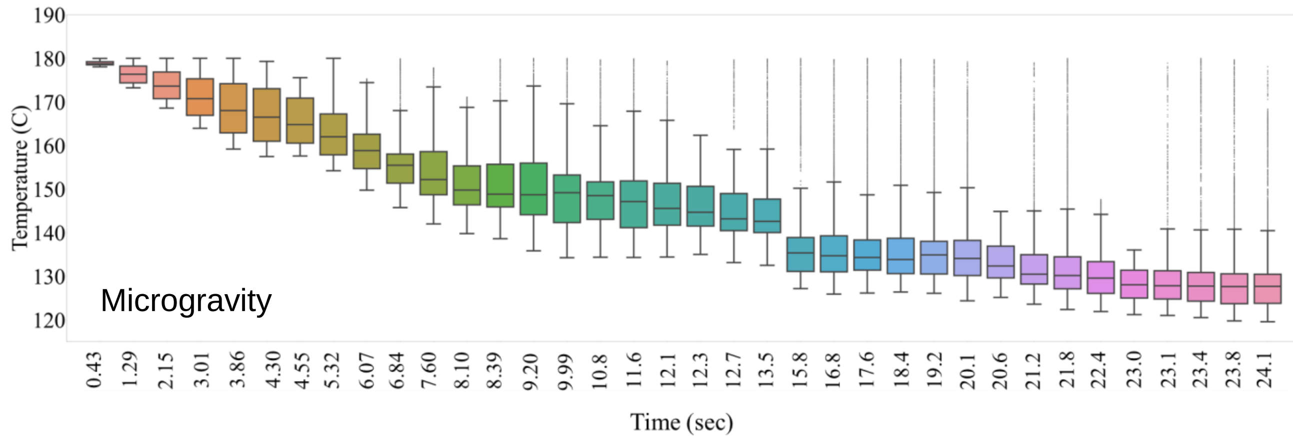


ON-EARTH V/S MICROGRAVITY

On-Earth v/s Microgravity PCL Printing

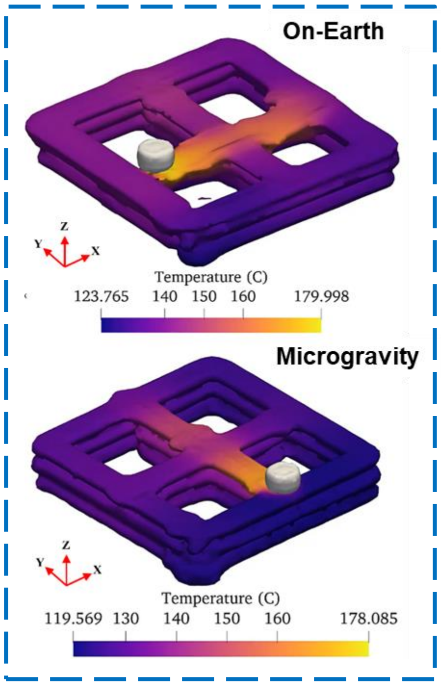


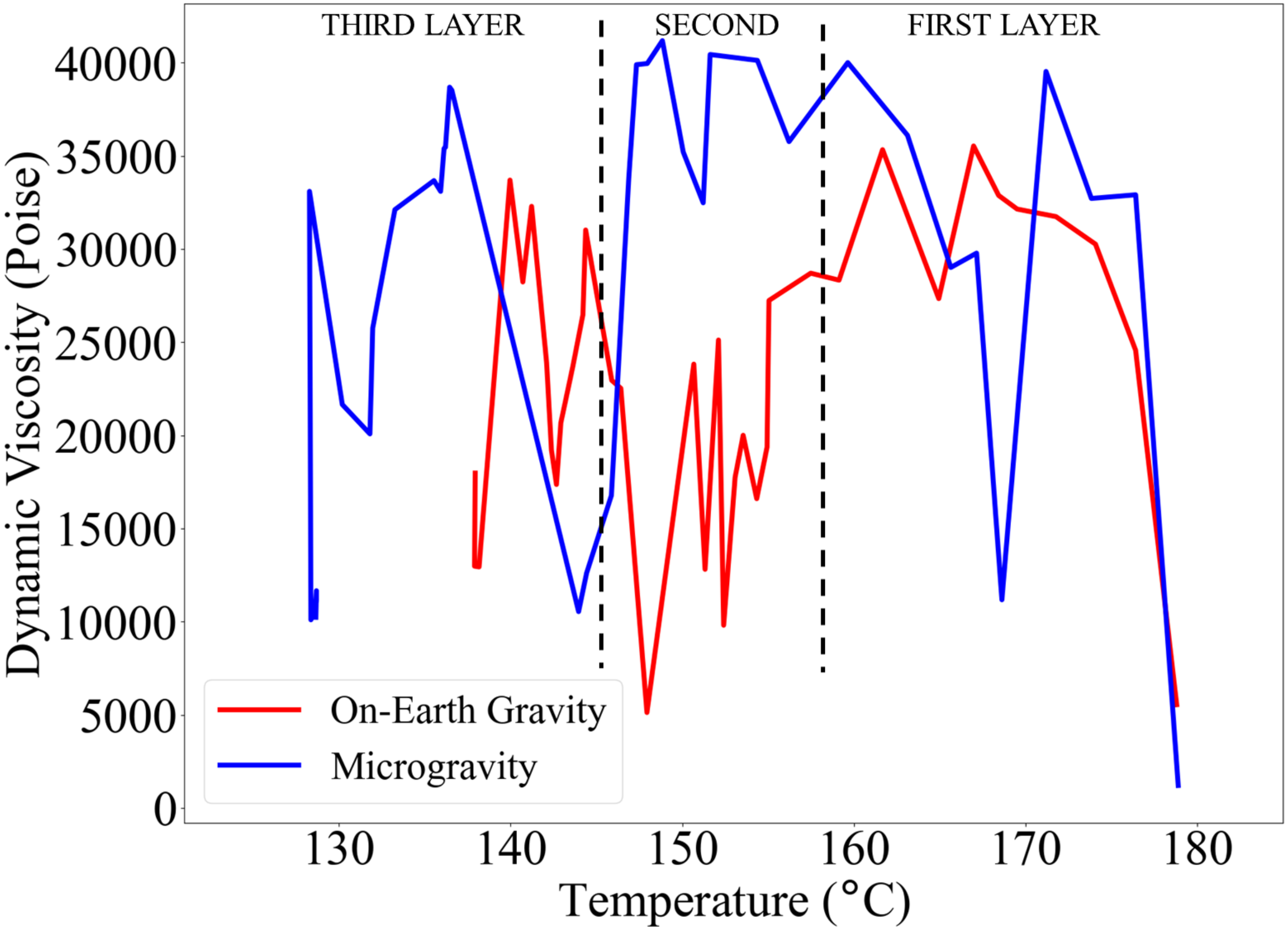




ON-EARTH V/S MICROGRAVITY

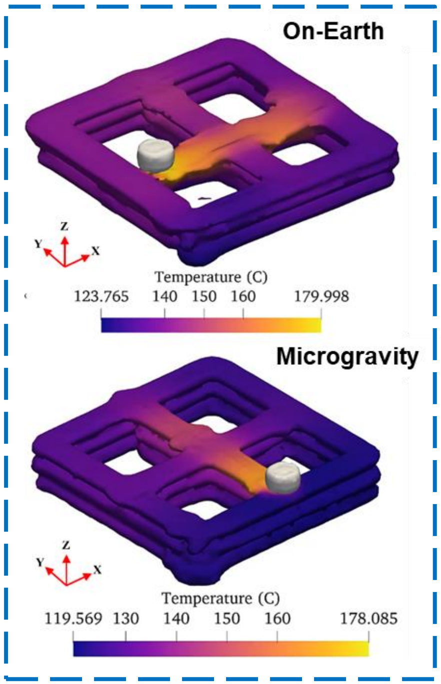
On-Earth v/s Microgravity PCL Printing

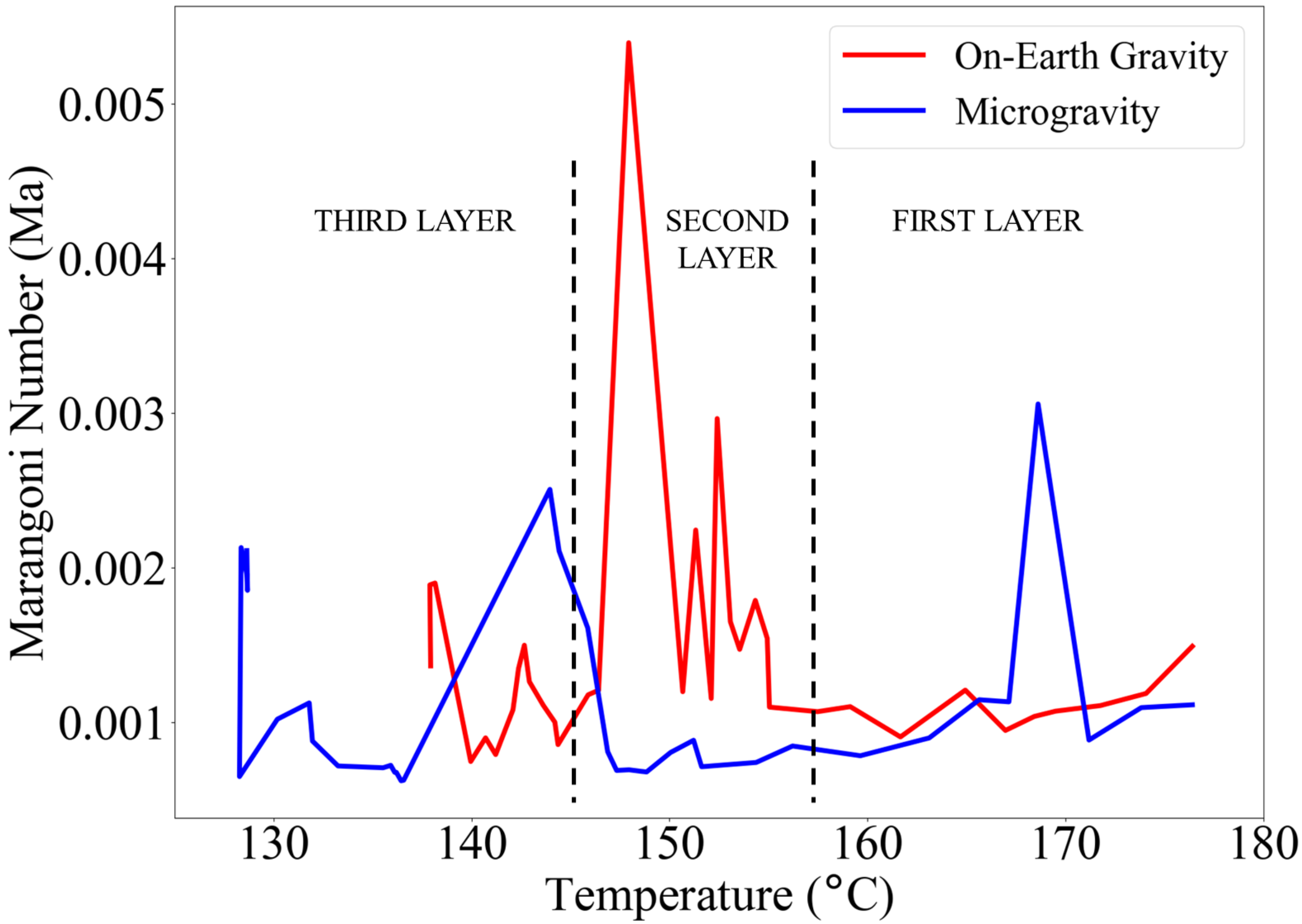




ON-EARTH V/S MICROGRAVITY

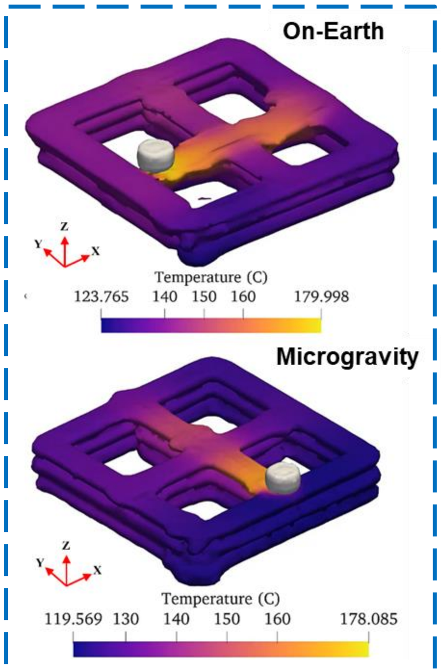
On-Earth v/s Microgravity PCL Printing

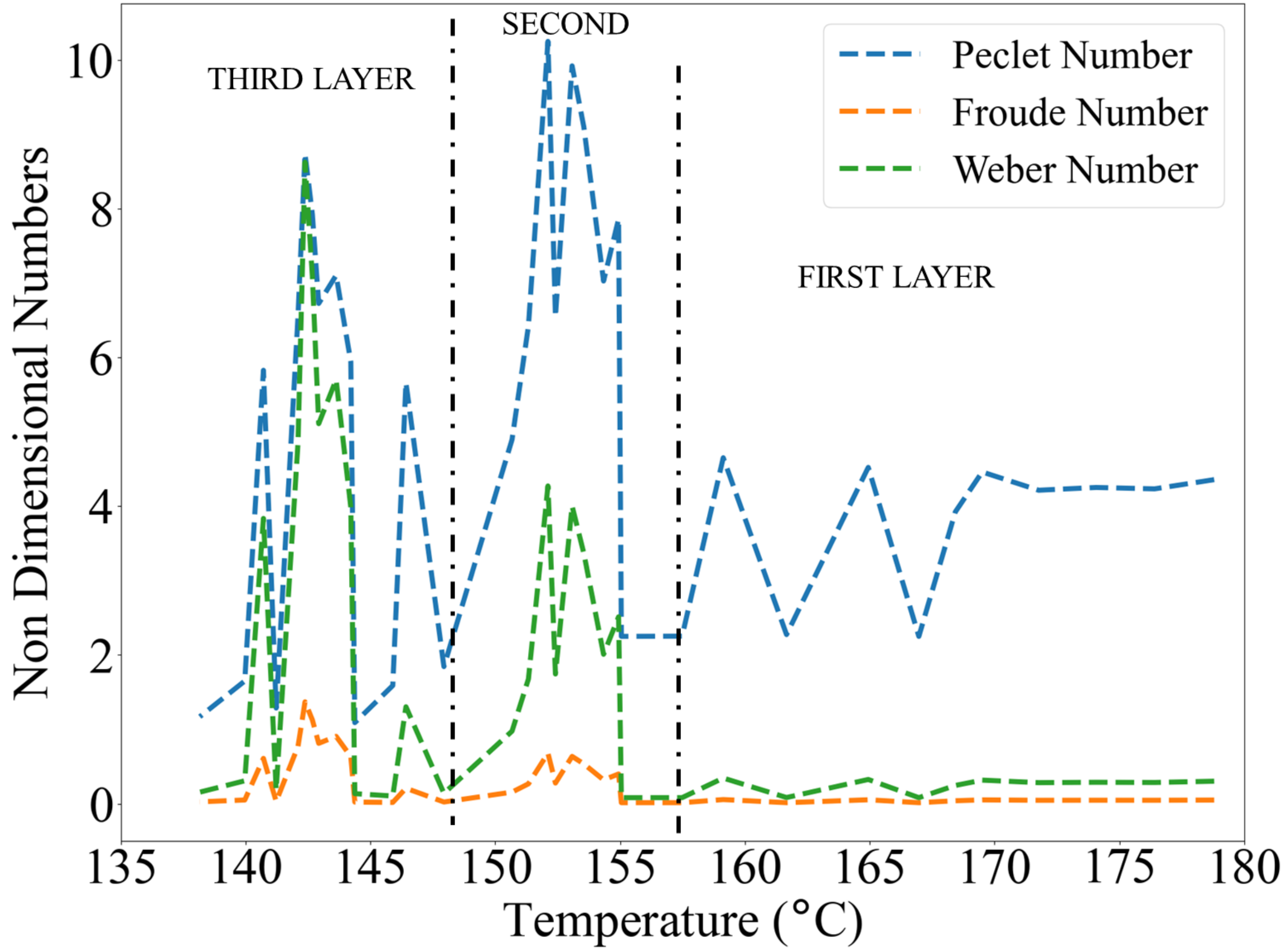




ON-EARTH V/S MICROGRAVITY

On-Earth PCL Printing

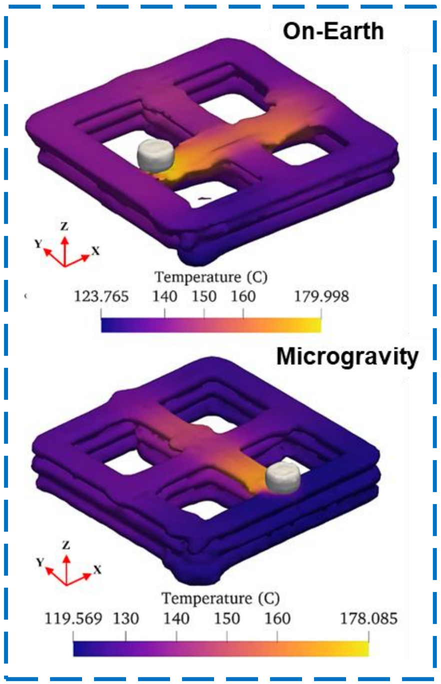


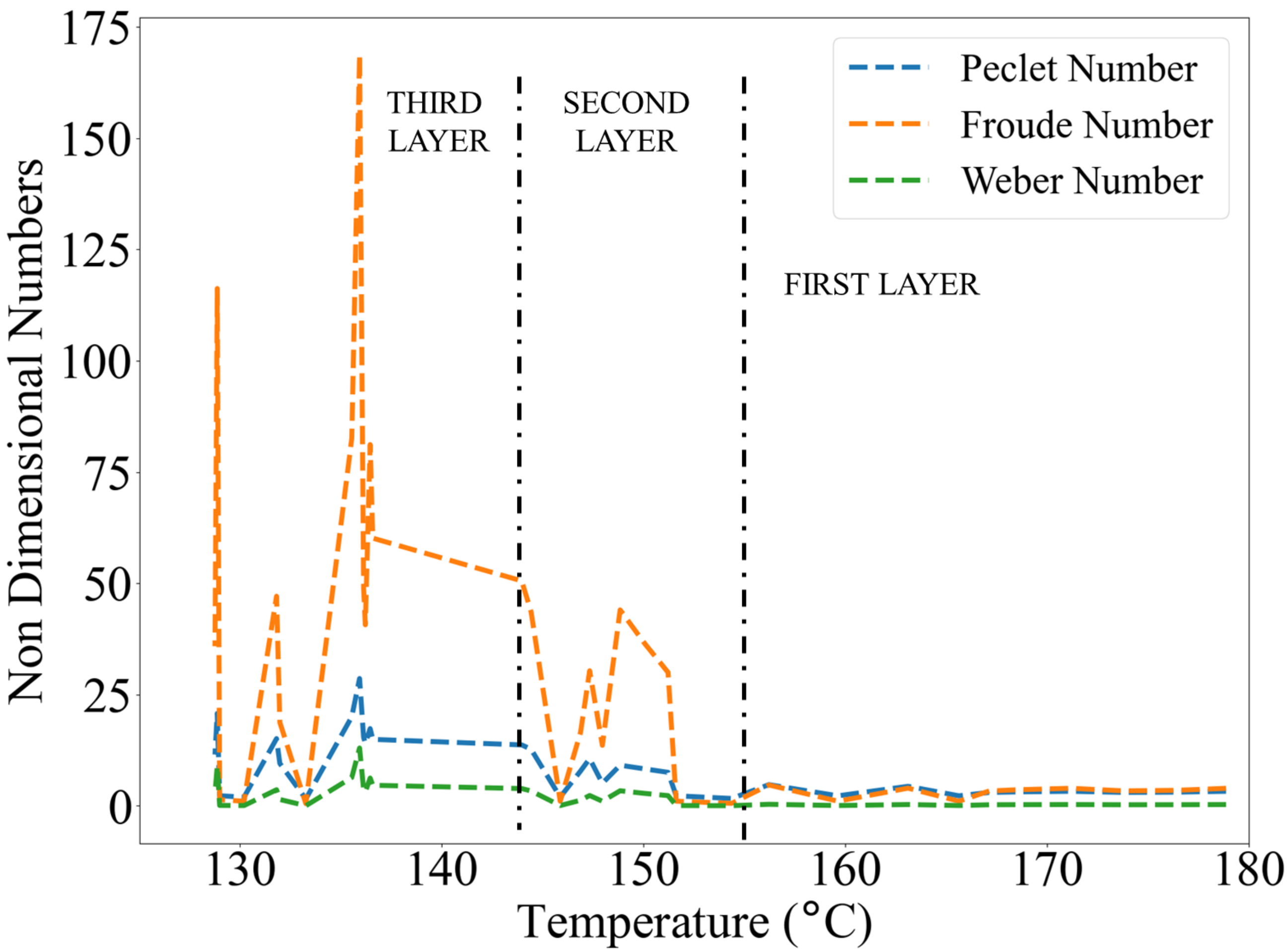


ON-EARTH V/S MICROGRAVITY

DISCUSSION

Microgravity PCL Printing





ON-**E**ARTH V/S **M**ICROGRAVITY

CONCLUSION

Effectively used **on-earth-based modeling** considerations to predict the microgravity conditions for extrusion bioprinting of highly viscous fluids like PCL polymers.

The model is **versatile** enough to expand to **multi-layer** and **multi-track** simulations and compelling enough to study the influence of four different forces such as **gravity/buoyancy force, inertia force, viscous force, and surface tension** on the printing process.

The **shape** of the PCL cross-section **on-earth** conditions varies between **oval** and **elliptical** whereas it varies between **Rhombus** and **oval** under **microgravity**.

Under **microgravity** conditions, the **shape** and **size** of the printed layers at their desired design were better **maintained** compared to on-earth conditions.

Under **microgravity**, **uniformity** of the **shape** and increase in the **size** of printed layers are **independent** of the process parameters and can be utilized for regenerative medicines applications.

The **highly viscous fluids** that are **more favorable** materials for extrusion bioprinting in Space **microgravity** conditions can be effectively modeled and studied using CFD modeling.

ON-EARTH V/S MICROGRAVITY

CONCLUSION

Thank You

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<<< ANY QUESTIONS? >>>