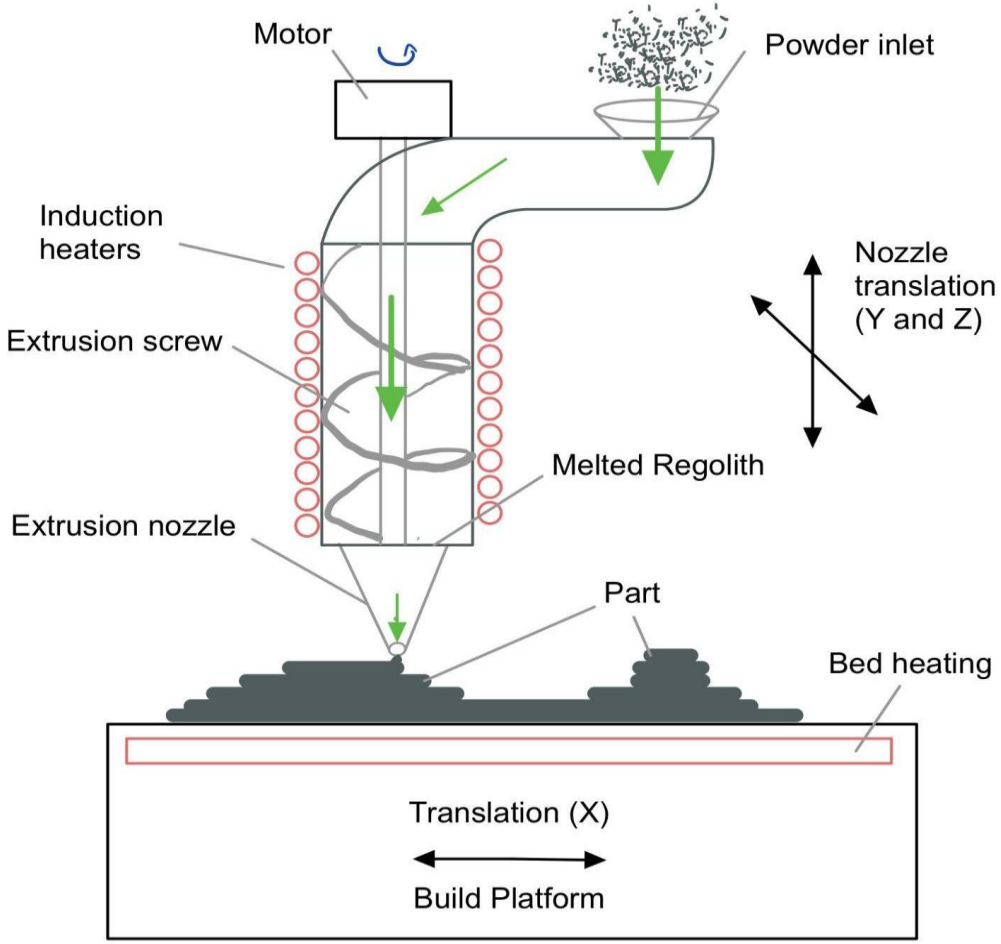
Building Amongst the Stars

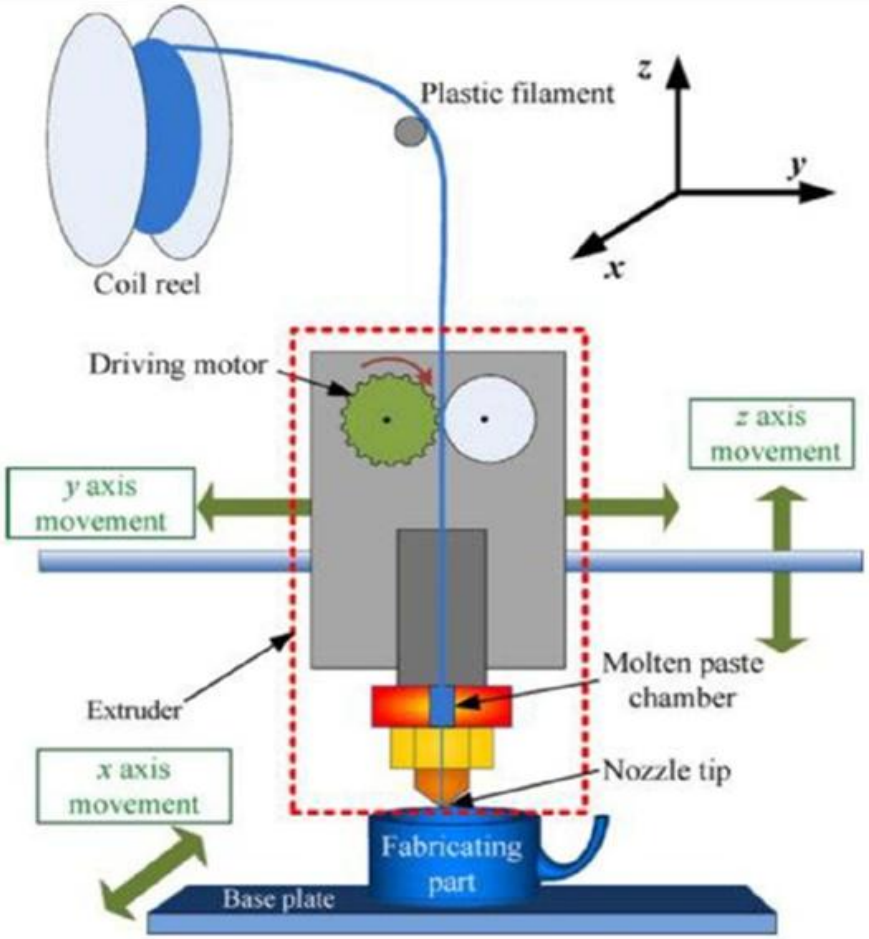
F25 – NP – Design and Analysis of Extrusion Mechanics for an Adapted Fused Deposition Modeling System on Asteroid 16–Psyche

Luke Hampson, William Massa, Elena Vazquez, Jackson Wise, Zachary Wright

2025–2026 Capstone Design (MCHE 4910/4911)

College of Engineering
UNIVERSITY OF GEORGIA





EXPERIMENTAL DESIGN

Evaluation Criteria, Simulation, and Analysis

UNIVERSITY OF GEORGIA

Proposed AM System

From our engineering decision making tools (QFD, FMEA, decision matrix), our team decided to explore the **Adapted Metal FDM** process and its deliverables for further development, after considering…

- VACUUM COMPATIBILITY
- LOW POWER CONSUMPTION
- MATERIAL USAGE
- POTENTIAL AUTOMATION
- LOW RELIANCE ON PBM
- LOW DESIGN COSTS
- SIMPLICITY / TRL

Features of Initial Prototype

To achieve a successfully adapted FDM process that accounts for Psyche's unique conditions, we needed a additive manufacturing system that…

- Promotes bed-adhesion
- Prevents clogging and extrusion failure modes
- Extrudes without reliance on gravity
- Accounts for thermal cycling, vacuum, and other conditions

Therefore, our model needed to be able to…

- Simulate thermal and fluid behavior
- Compare geometry between designs
- Model the extrusion mechanism
- Communicate results and system feasibility

V&V Plans

As our project is to understand the feasibility of the system, our main focus is on the verification of our simulation with theoretized models. Such verification processes focus on…

- **Functionality** – How does the system operate under conditions?
- **Design Sustainability** – How long can optimal functionality be sustained?
- **Quality** – What is the precision/accuracy of parts created?
- **Safety** – How much (if any) stress does the operation provide to the entire system?

A source of future development (out of the scope for this project) would be the validation of measurements found using real-world testing. Therefore, only proposed validation procedures have been created.

Evaluation Methodology

Measurements

- Pressure/Thermal stresses
- Die swelling

How to measure:

- Time dependent analysis of mass flow rate out of nozzle
- Pressure/Thermal contours

Analyze and Improve

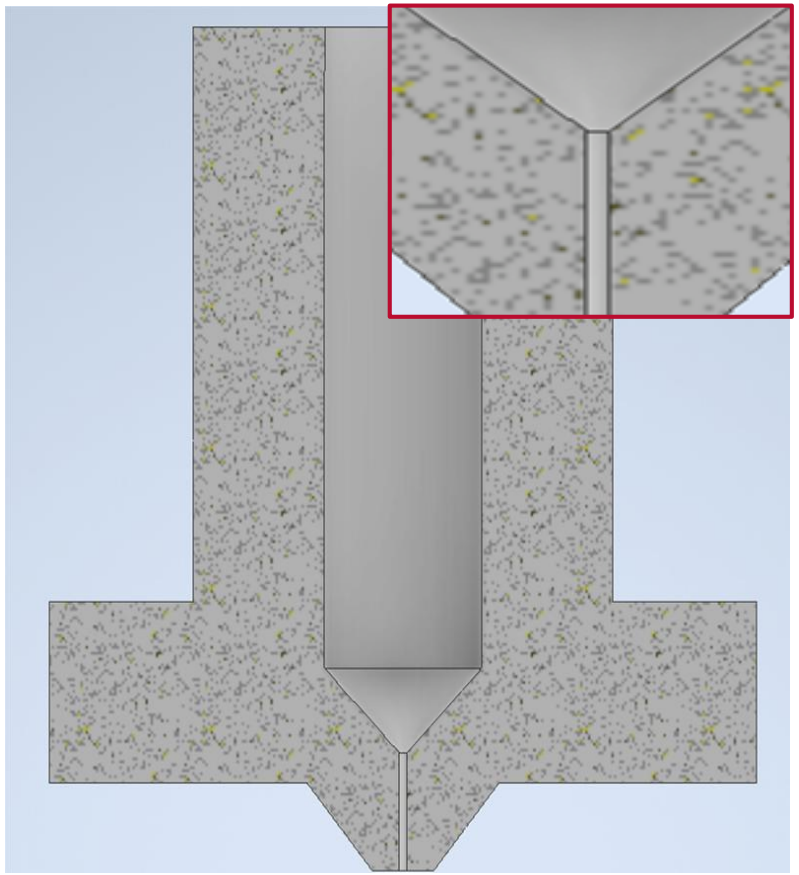
- Parameters of nozzle (which features minimize design failures)
- Areas of consistent design flaws across modeling (points to larger system optimization)

ANSYS Simulation

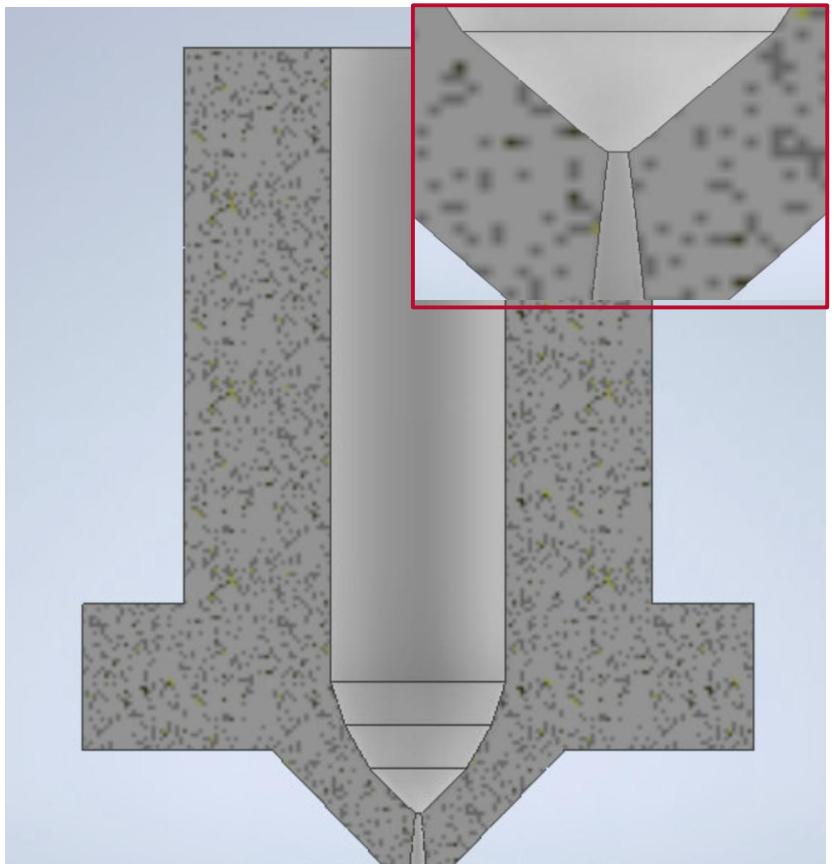
Set Up, Constraints, Modeling Assumption/Equations, and Results

Simulation Set Up → Geometries

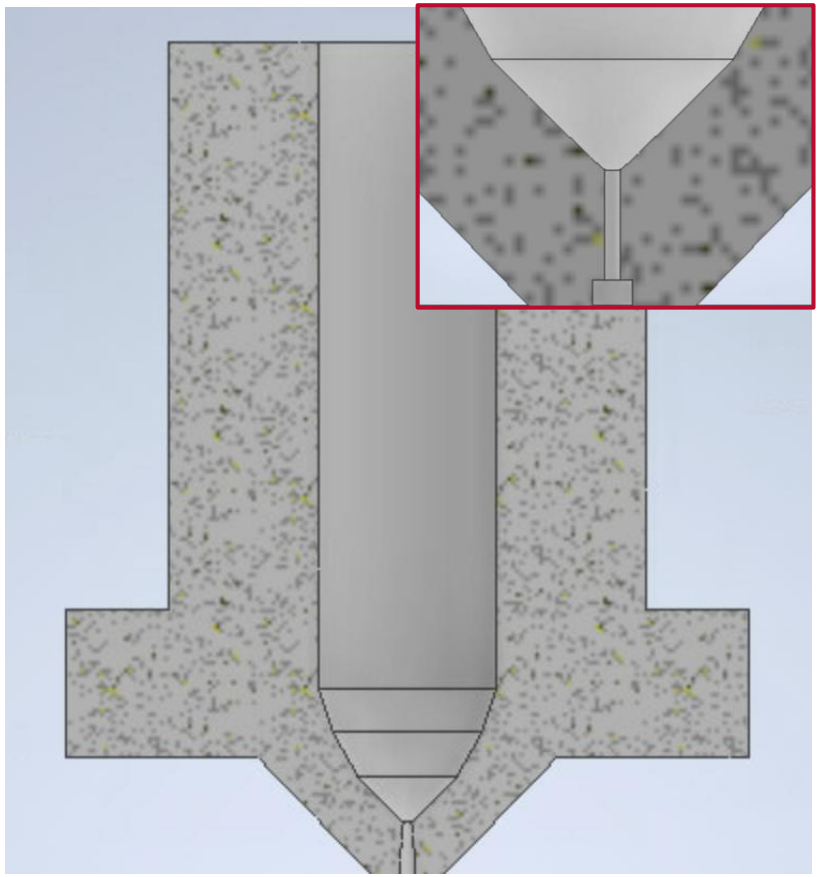
Converging



Converging-Diverging

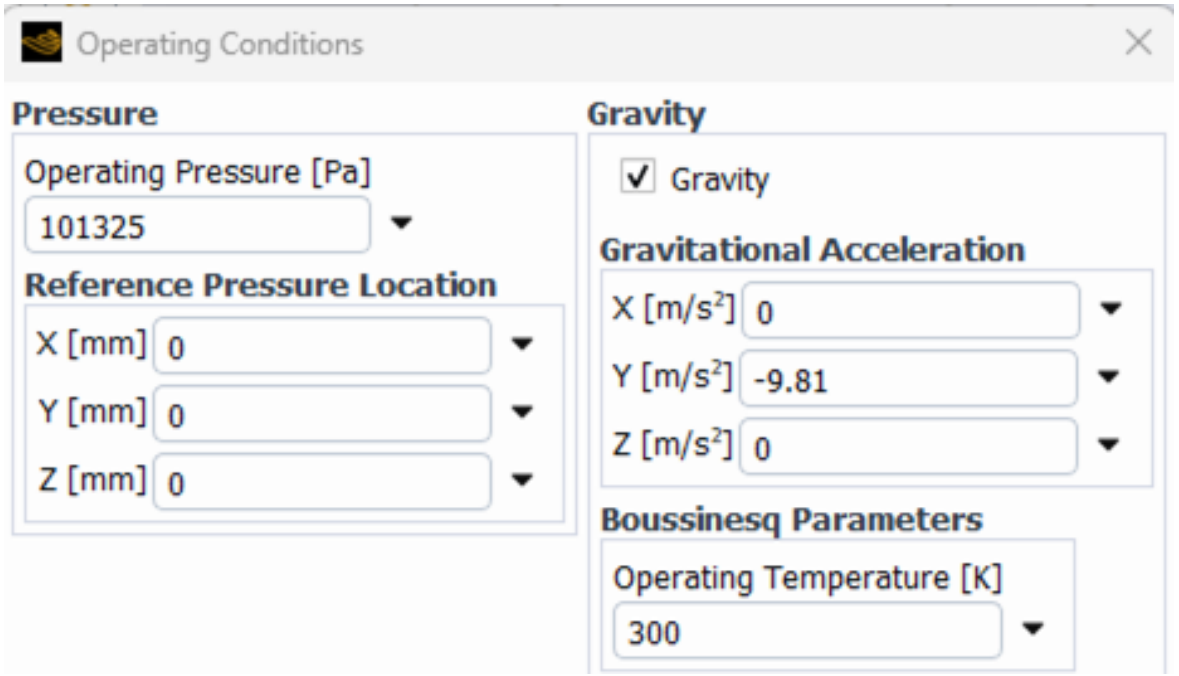


Converging-Stepped

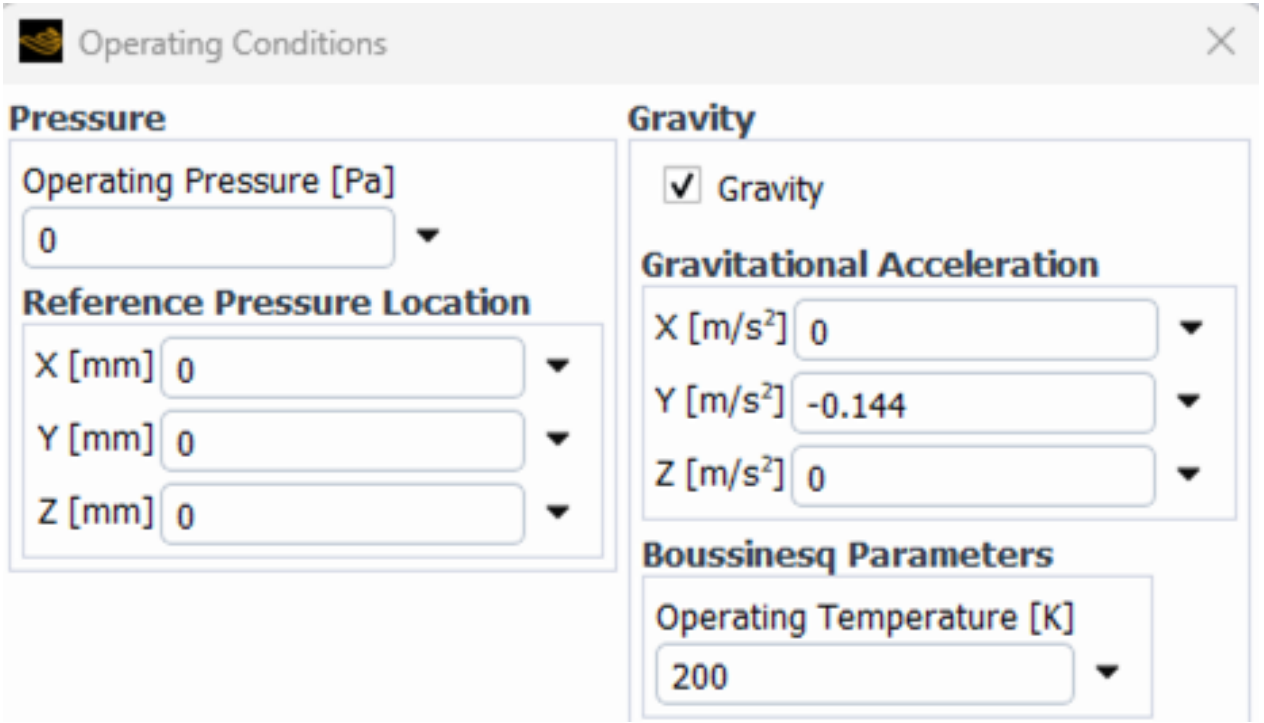


Simulation Set Up → System Setting

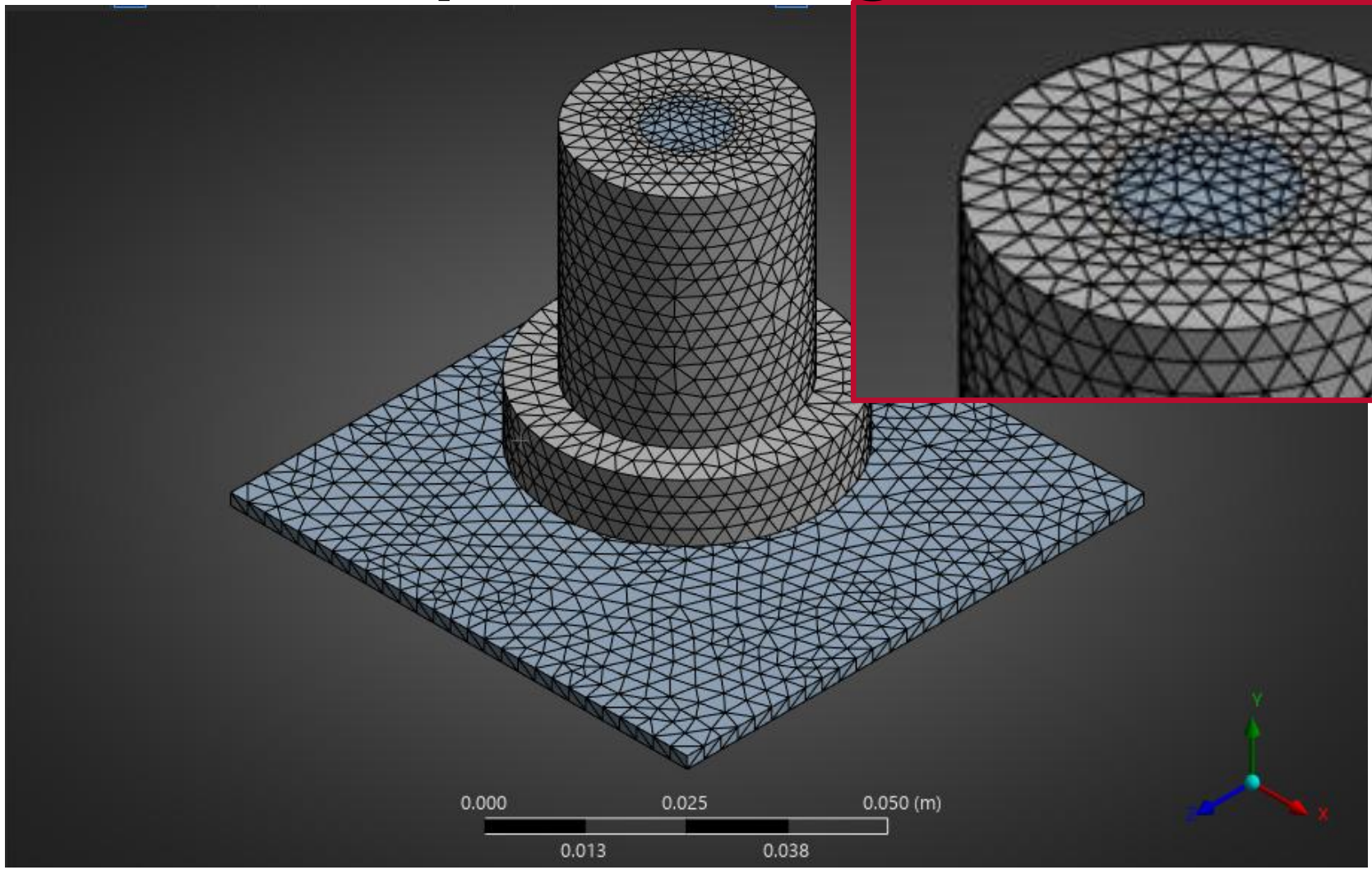
Earth-based



Psyche-based



Simulation Set Up → Meshing



Simulation Set Up → Meshing

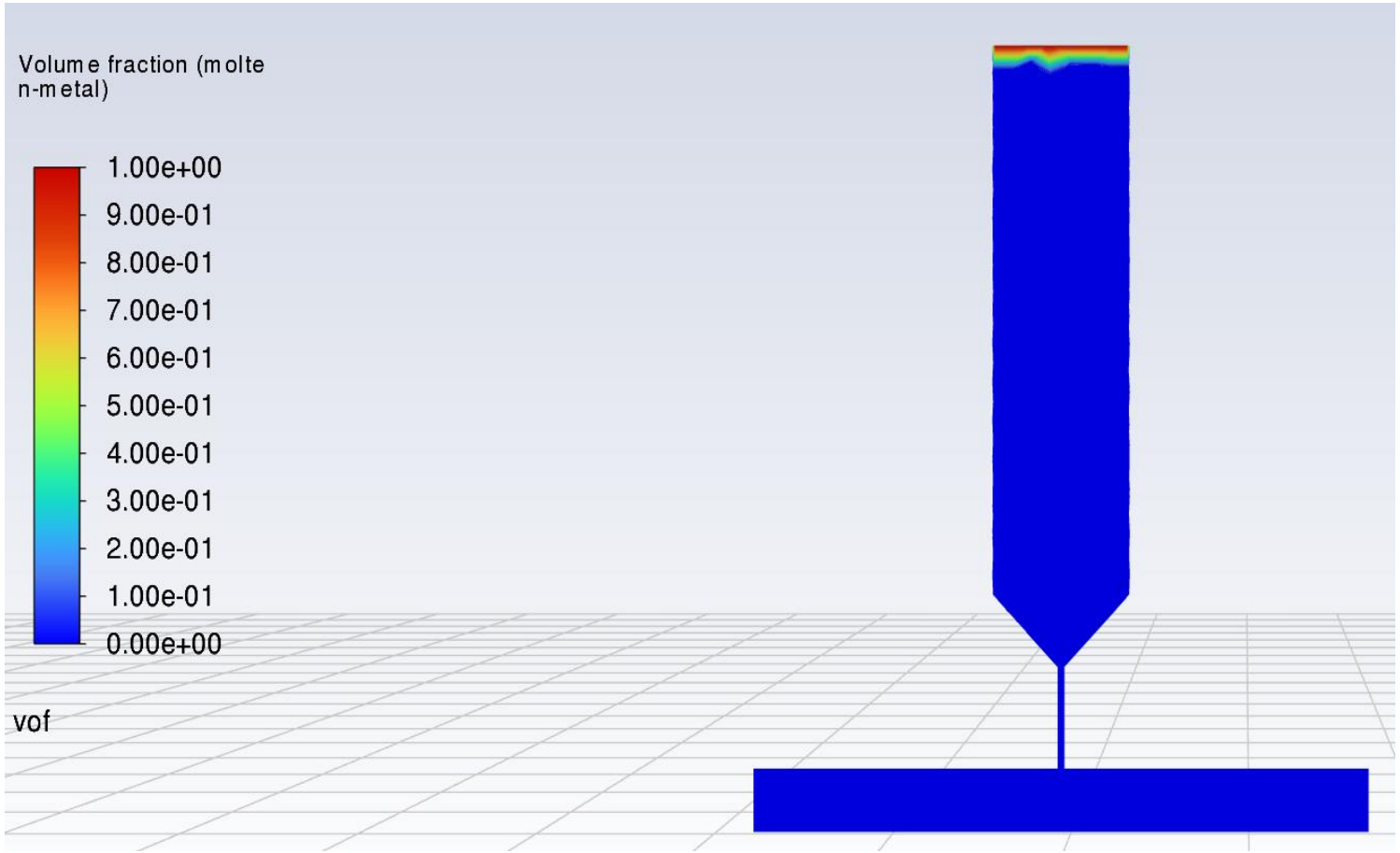
Sheet | ✓ Solid | ✓ Solid - Surface

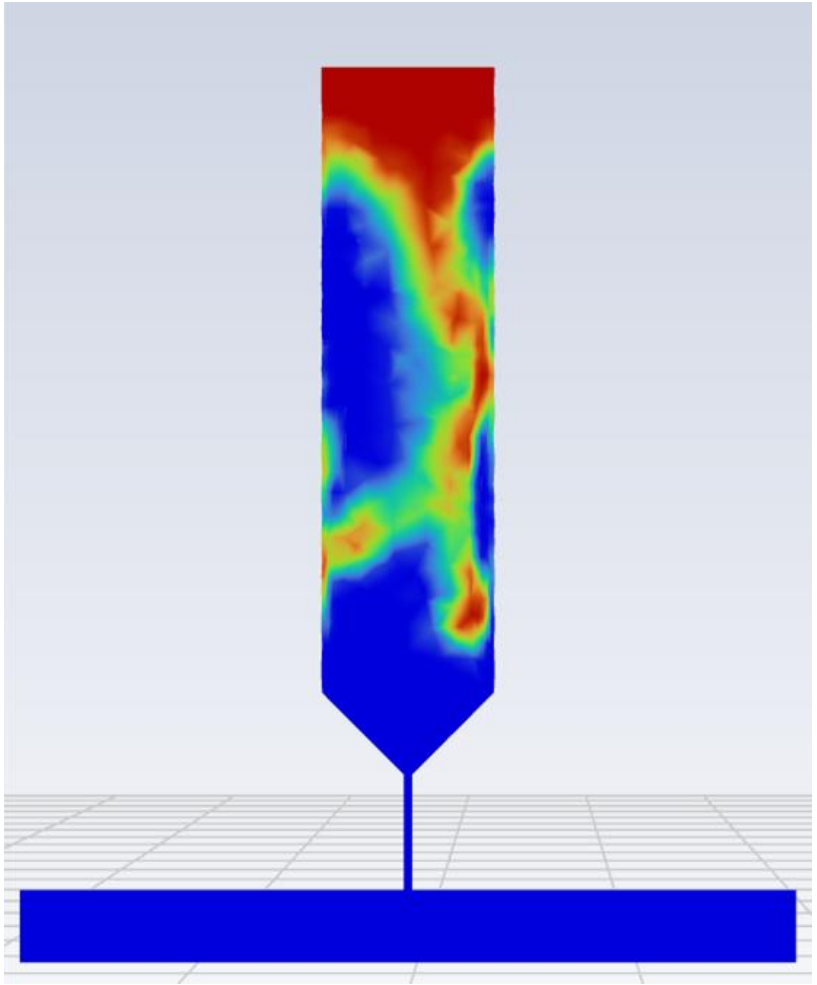
Error Check	Quality Criterion	Warning Limit	Error (Failure) Limit	Worst
	Max Aspect Ratio	Default (5)	Default (1000)	9.264
	Min Element Quality	Default (0.05)	Default (5e-04)	0.223
	Min Jacobian Ratio (Corner Nodes)	Default (0.05)	Default (0.025)	0.308
	Min Jacobian Ratio (Gauss Points)	Default (0.05)	Default (0.025)	0.655
	Max Element Edge Length	Default (0.064 m)	Default (0.128 m)	6.3e-03 m
	Max Corner Angle	Default (150 °)	Default (170 °)	156.22 °
	Min Element Edge Length	Default (6.4e-04 m)	Default (6.4e-05 m)	7.8e-05 m
	Max Skewness	Default (0.9)	Default (0.999)	0.98
	Min Tet Collapse	Default (0.1)	Default (1e-03)	0.19
	Max Warping Angle	Default (20 °)	Default (30 °)	NA

Sheet | ✓ Solid | ✓ Solid - Surface

Error Check	Quality Criterion	Warning Limit	Error (Failure) Limit	Worst
	Max Aspect Ratio	Default (5)	Default (1000)	3.129
	Max Tri Angle	Default (160 °)	Default (170 °)	118.905 °
	Min Element Edge Length	Default (6.4e-04 m)	Default (6.4e-05 m)	1e-04 m
	Min Tri Angle	Default (20 °)	Default (10 °)	20.524 °
	Max Skewness	Default (0.9)	Default (0.999)	0.692

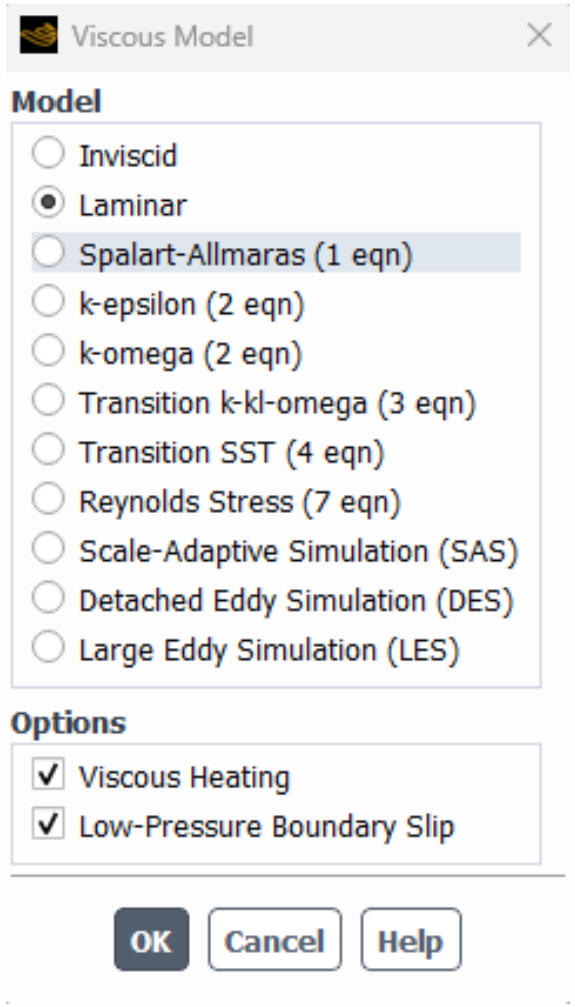
Simulation Enhancements → Viscosity Modeling





Failed Viscosity Model

Simulation Enhancements → Viscosity Modeling



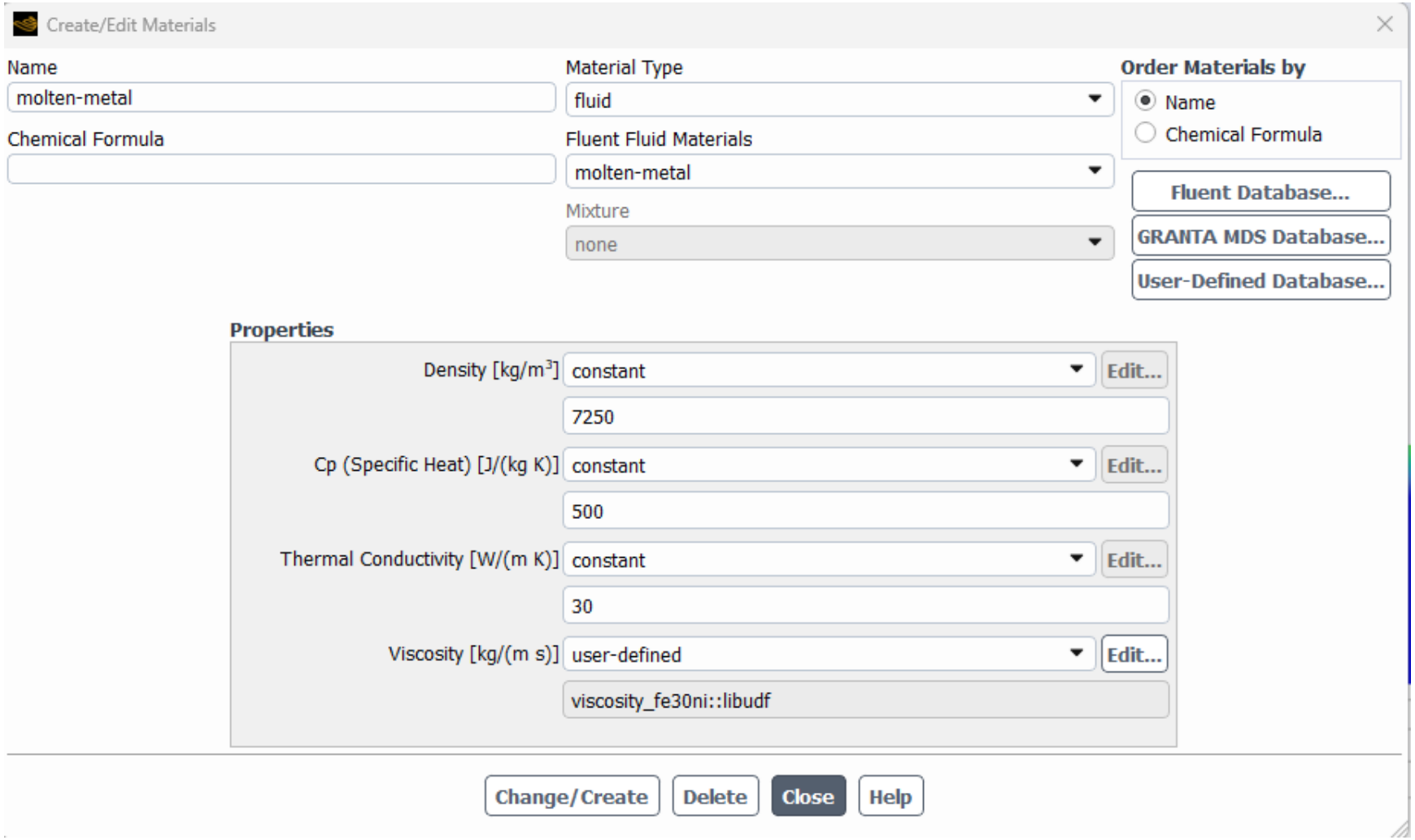
fe30ni_viscosity.c

File Edit View

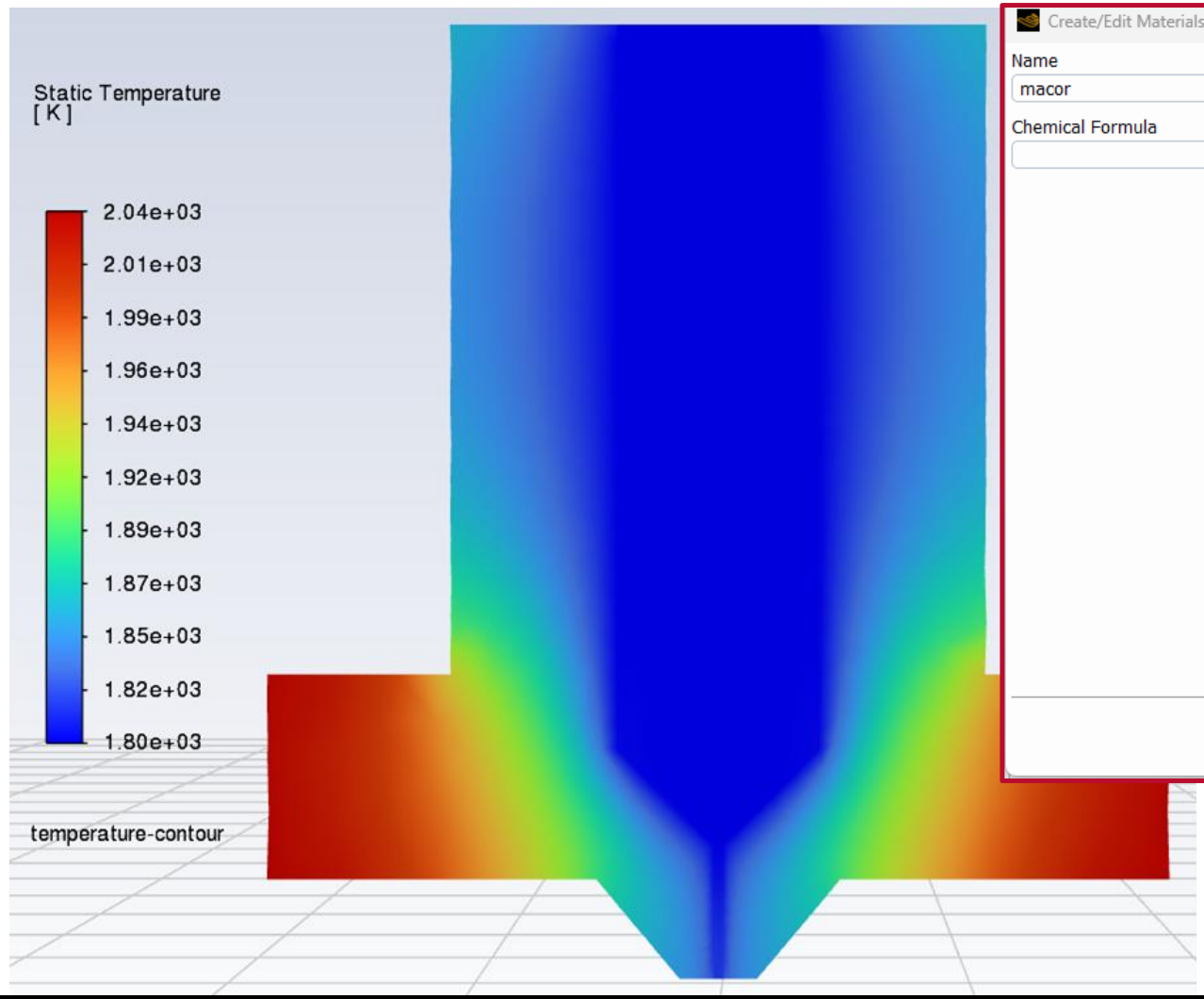
```
#include "udf.h"

DEFINE_PROPERTY(viscosity_fe30ni, c, t)
{
    real T = C_T(c,t);  // Temperature in Kelvin
    real mu;

    mu = 2.5e-4 * exp(58000.0 / (8.314 * T));

    return mu; // viscosity in Pa·s
}
```

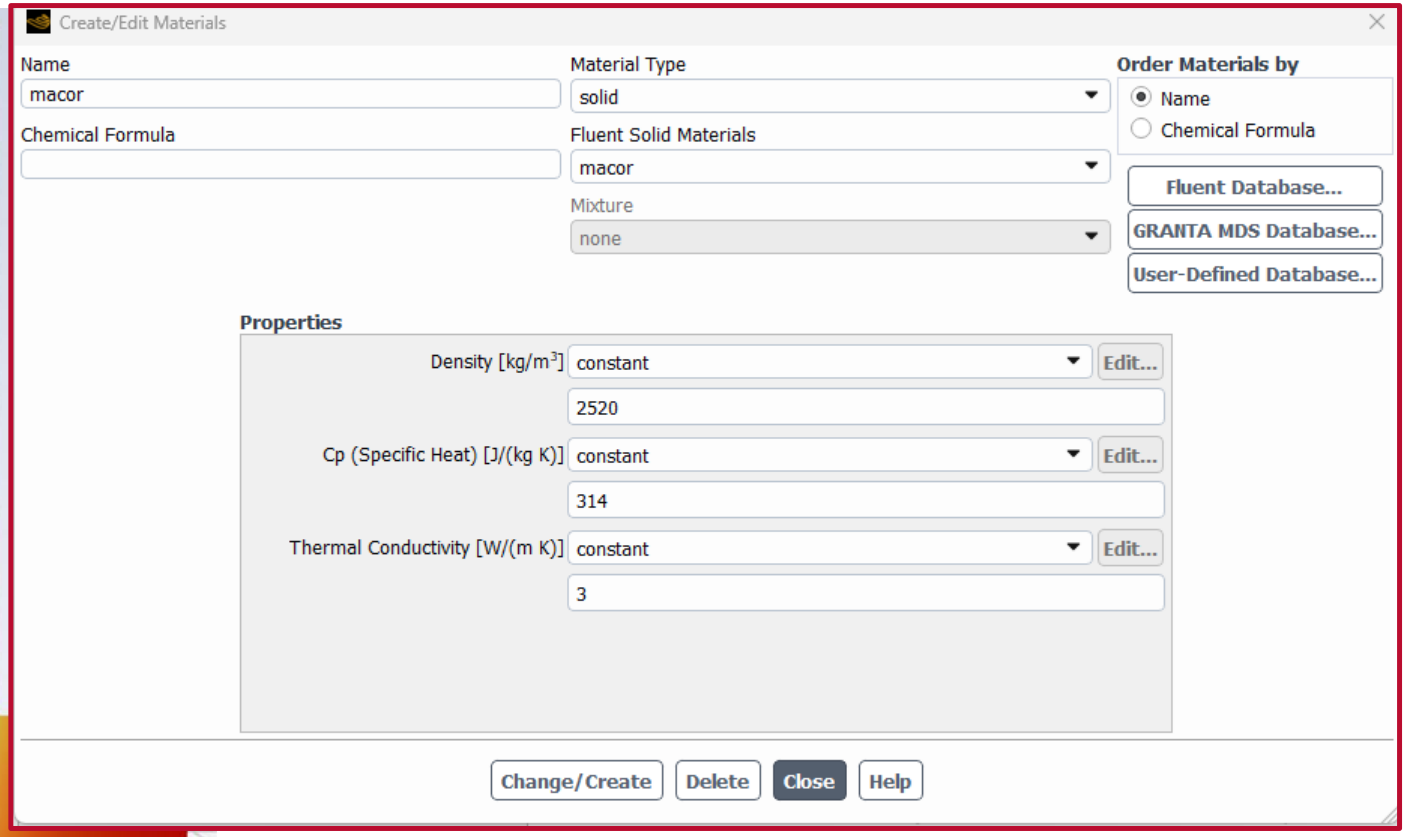
Arrhenius Model

Simulation Enhancements → Properties



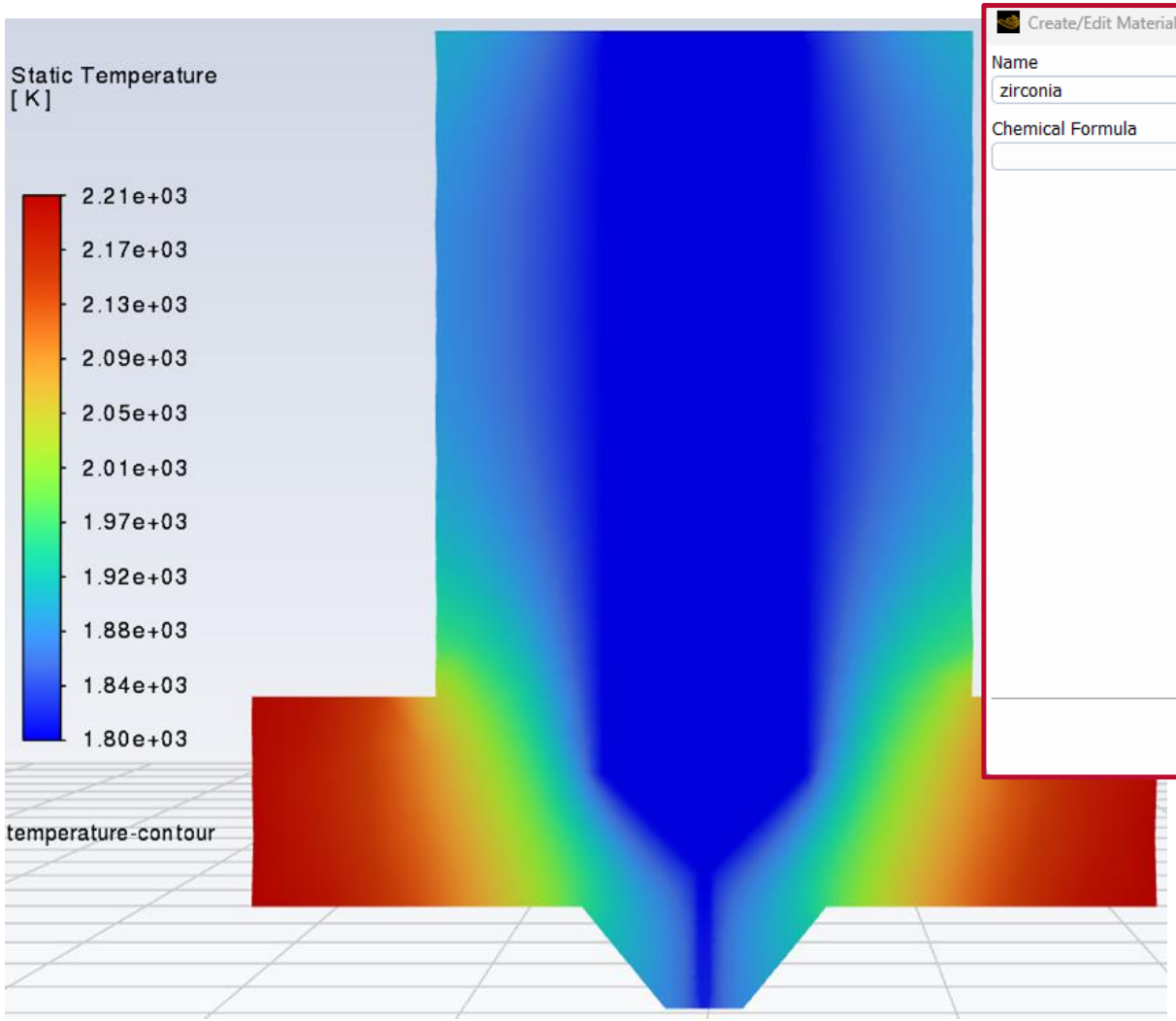
Simulation Enhancements → Properties

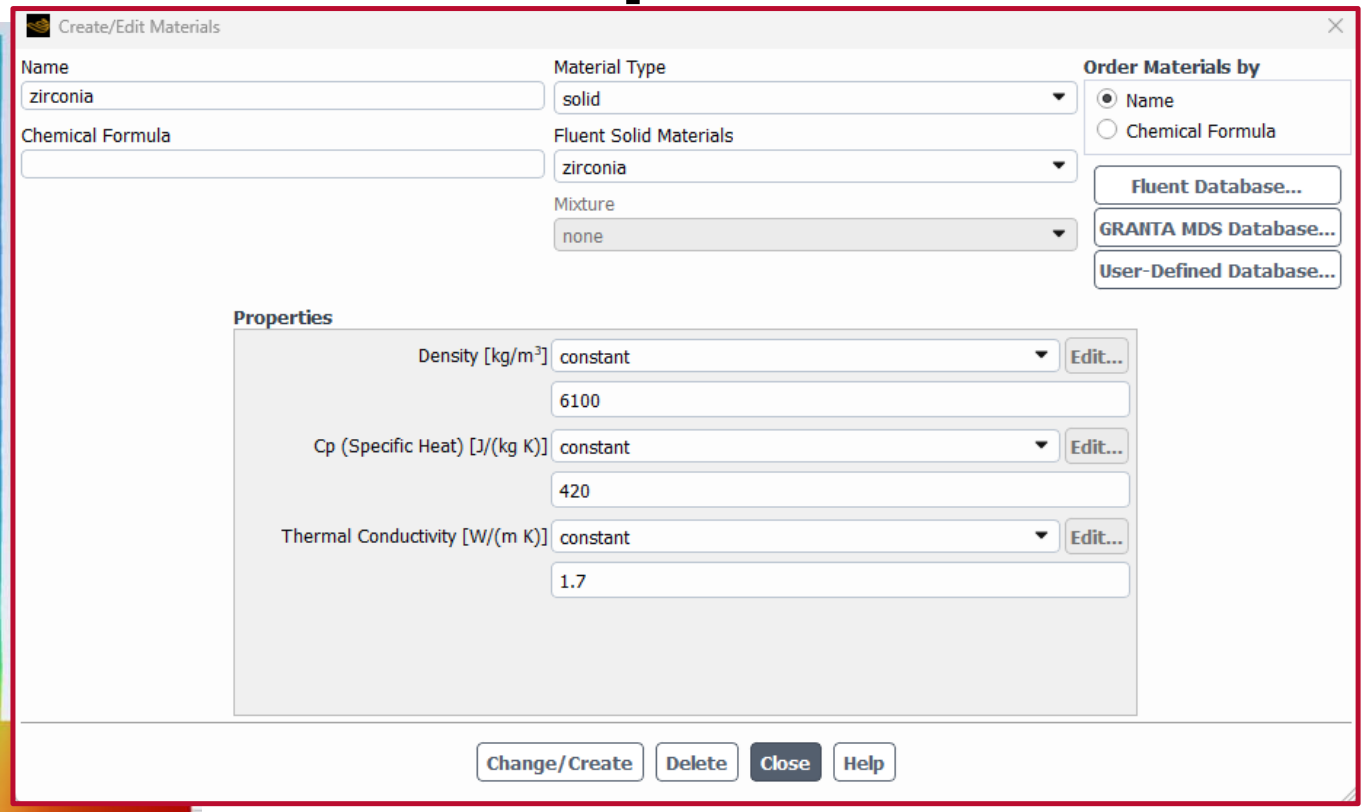




Macor Nozzle

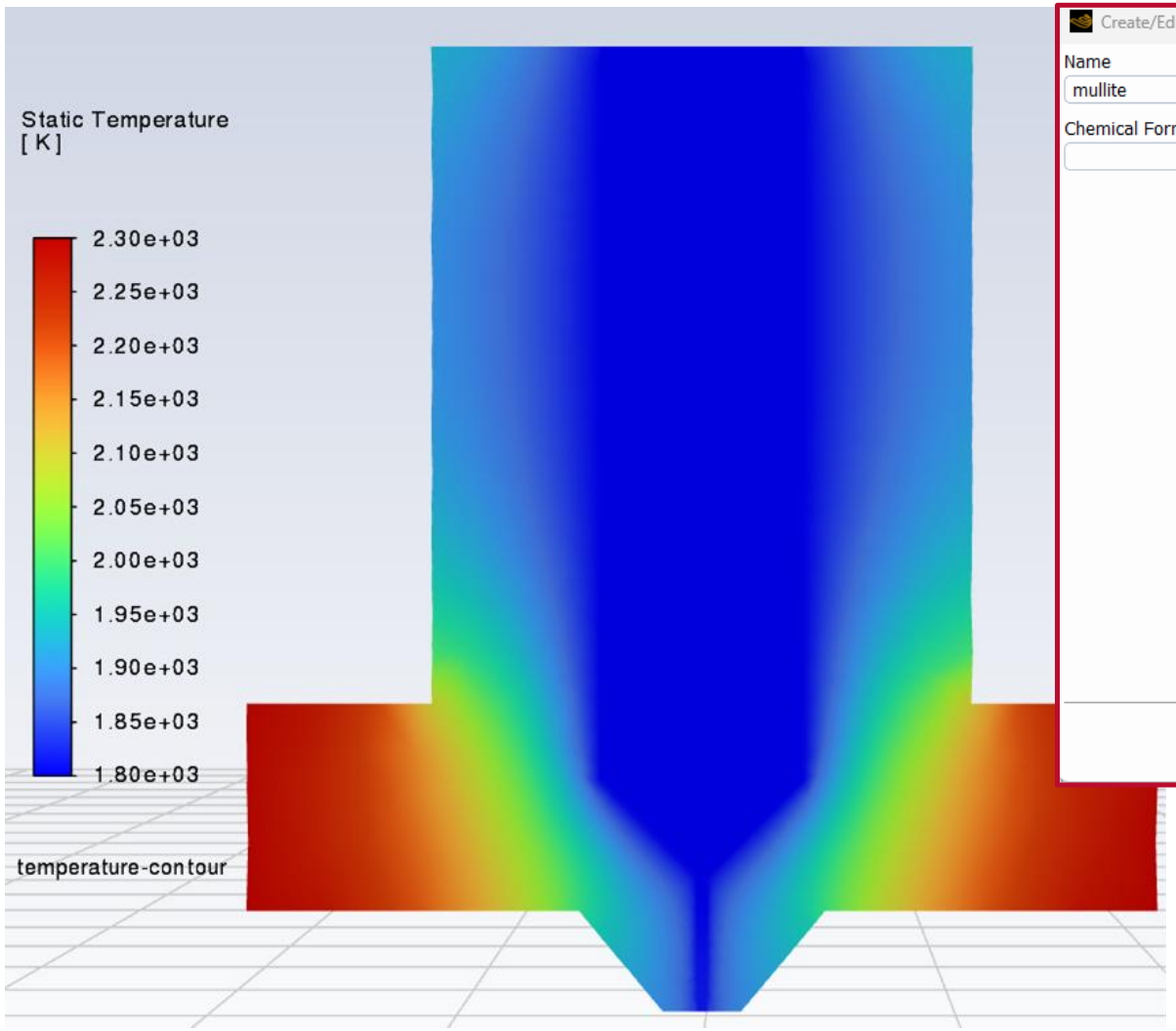
Simulation Enhancements → Properties

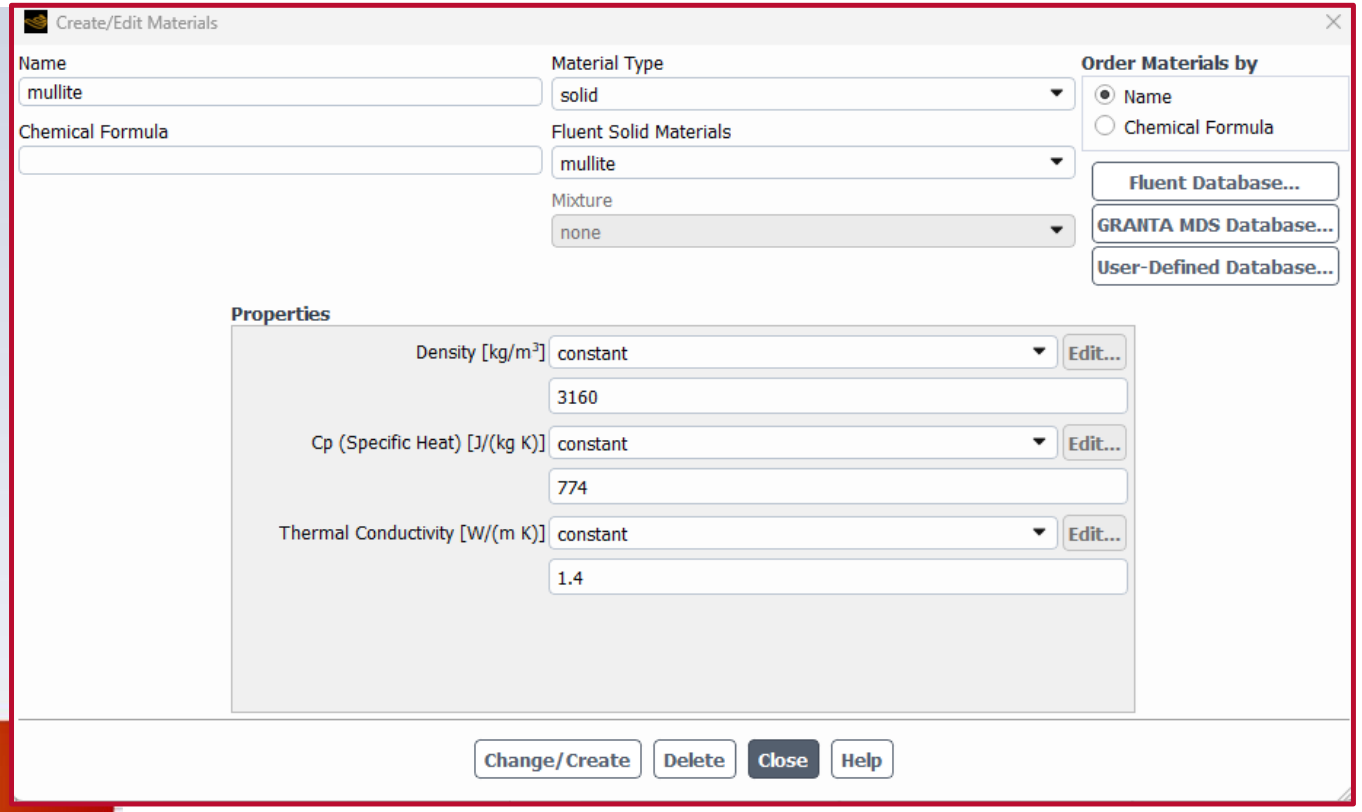




Zirconia Nozzle

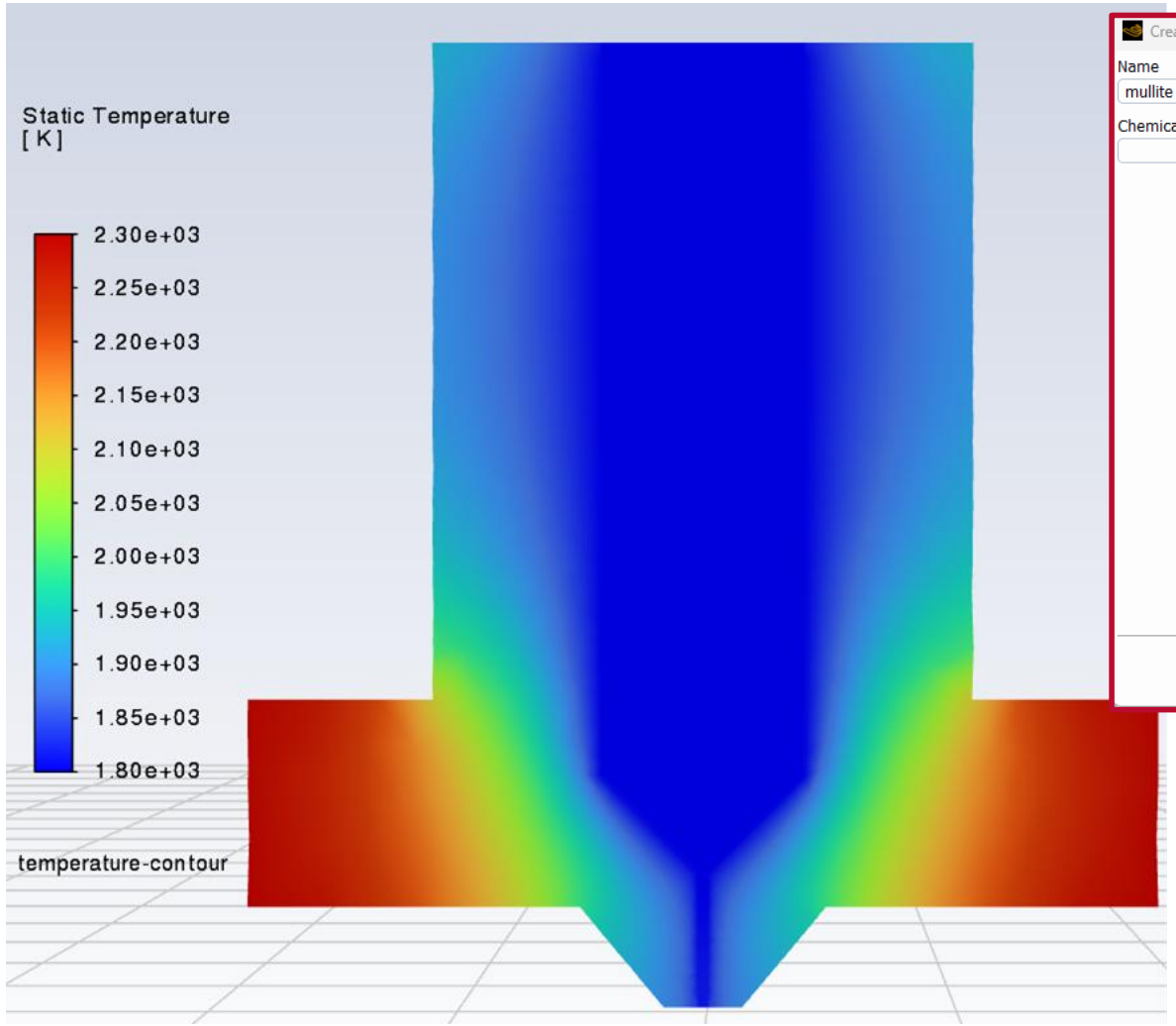
Simulation Enhancements → Properties

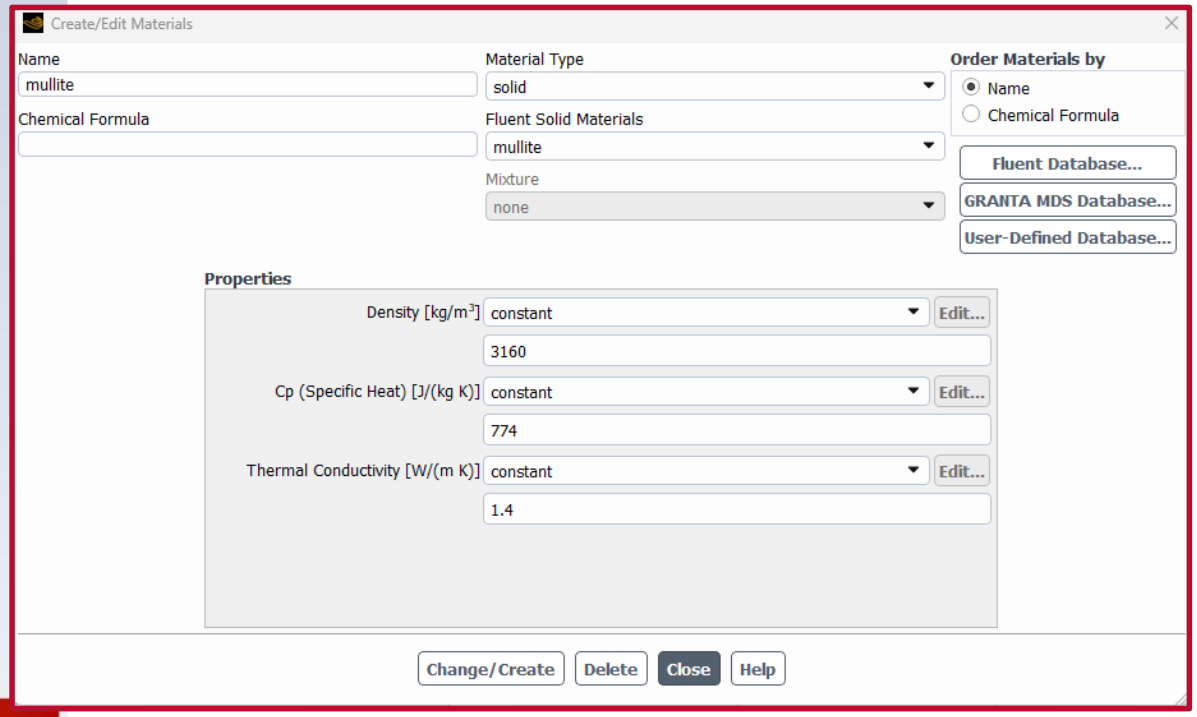




Mullite Nozzle

Simulation Enhancements → Properties

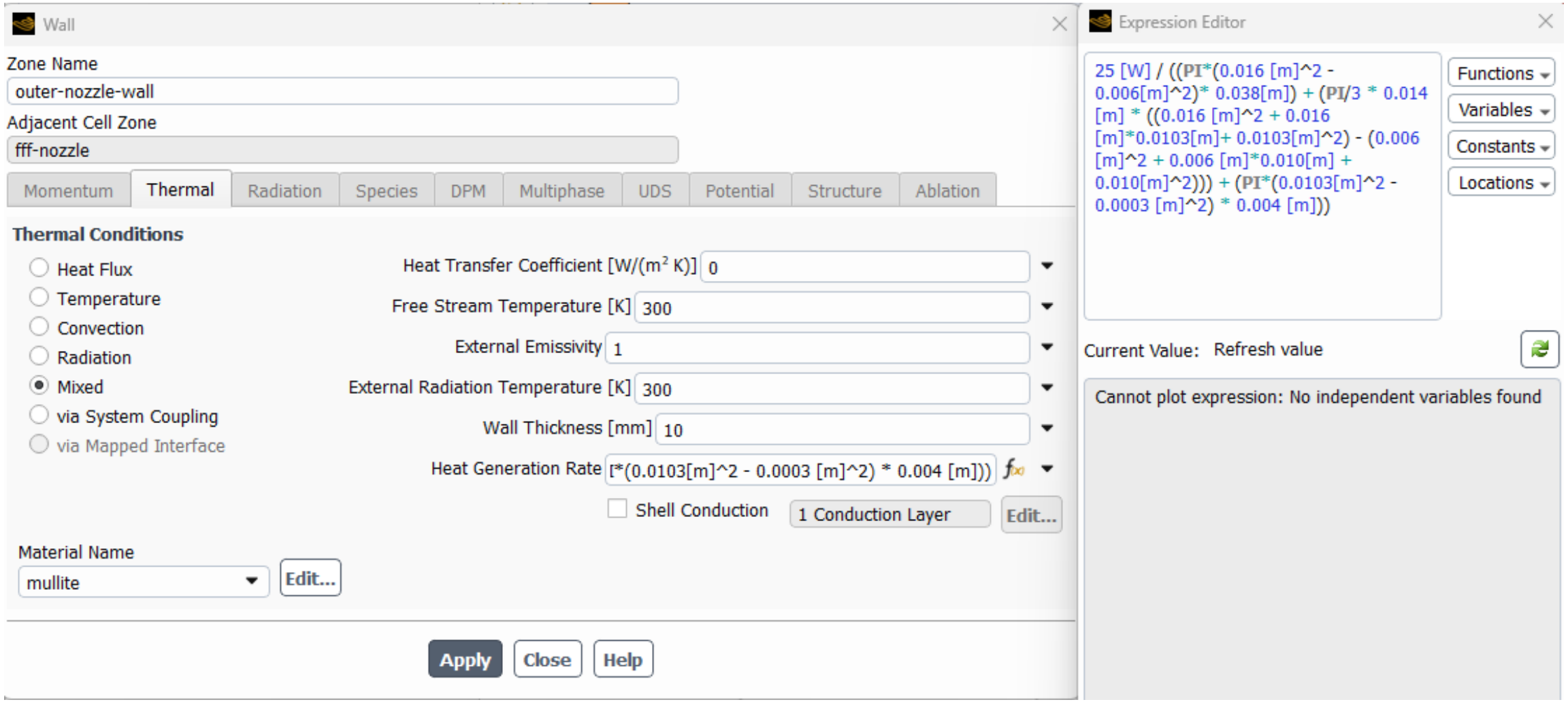




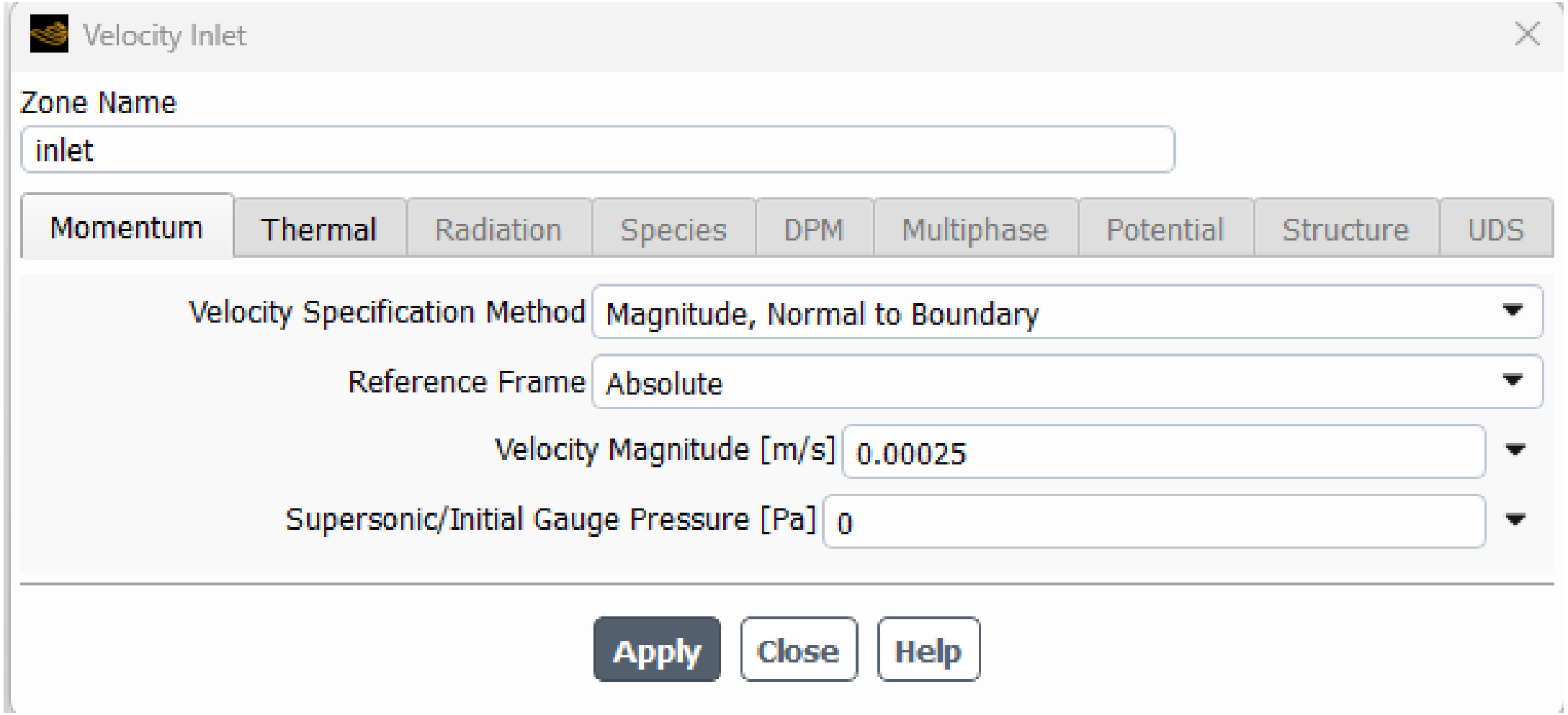
Mullite Nozzle

✓ *Selected Nozzle Property*

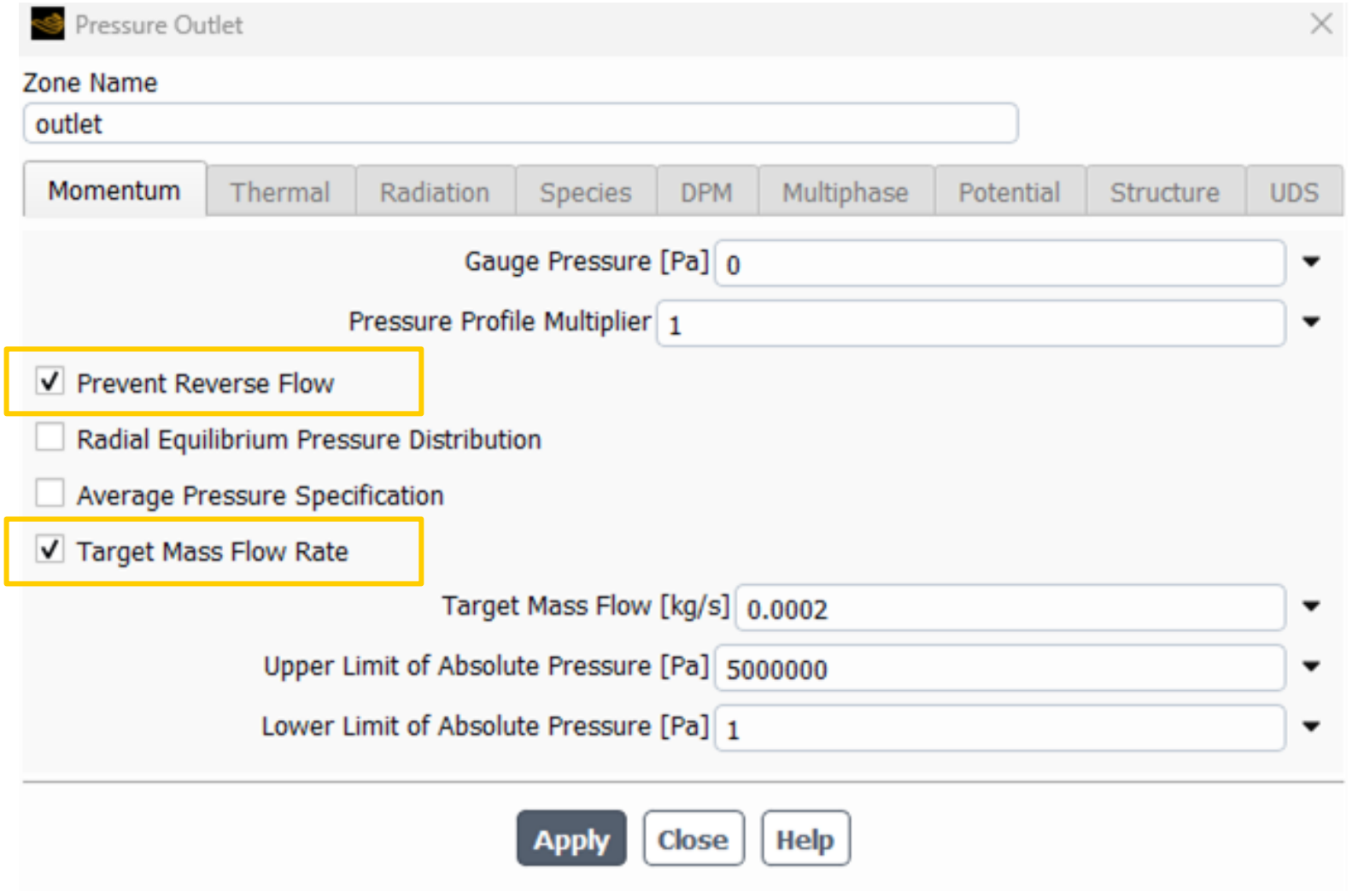
Simulation Enhancements → Heating



Simulation Process



Simulation Process

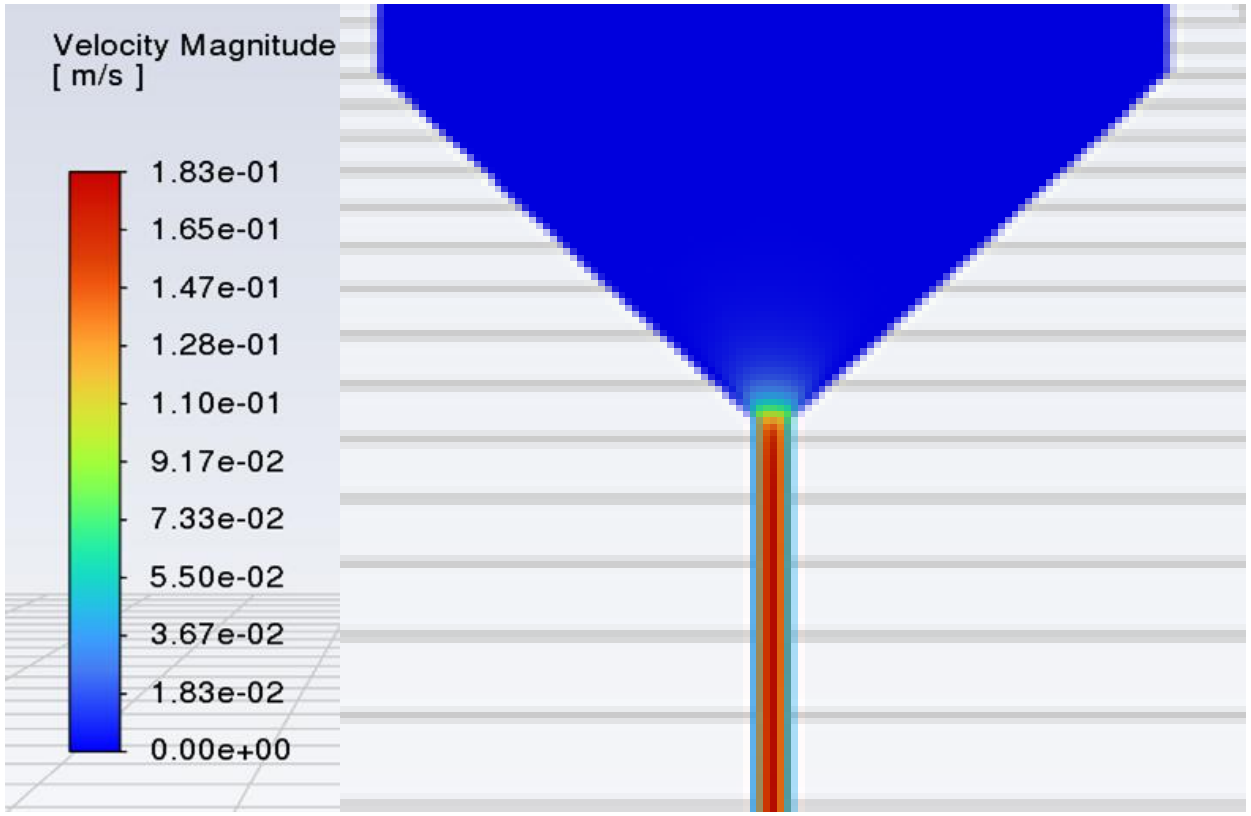


Results → Flow

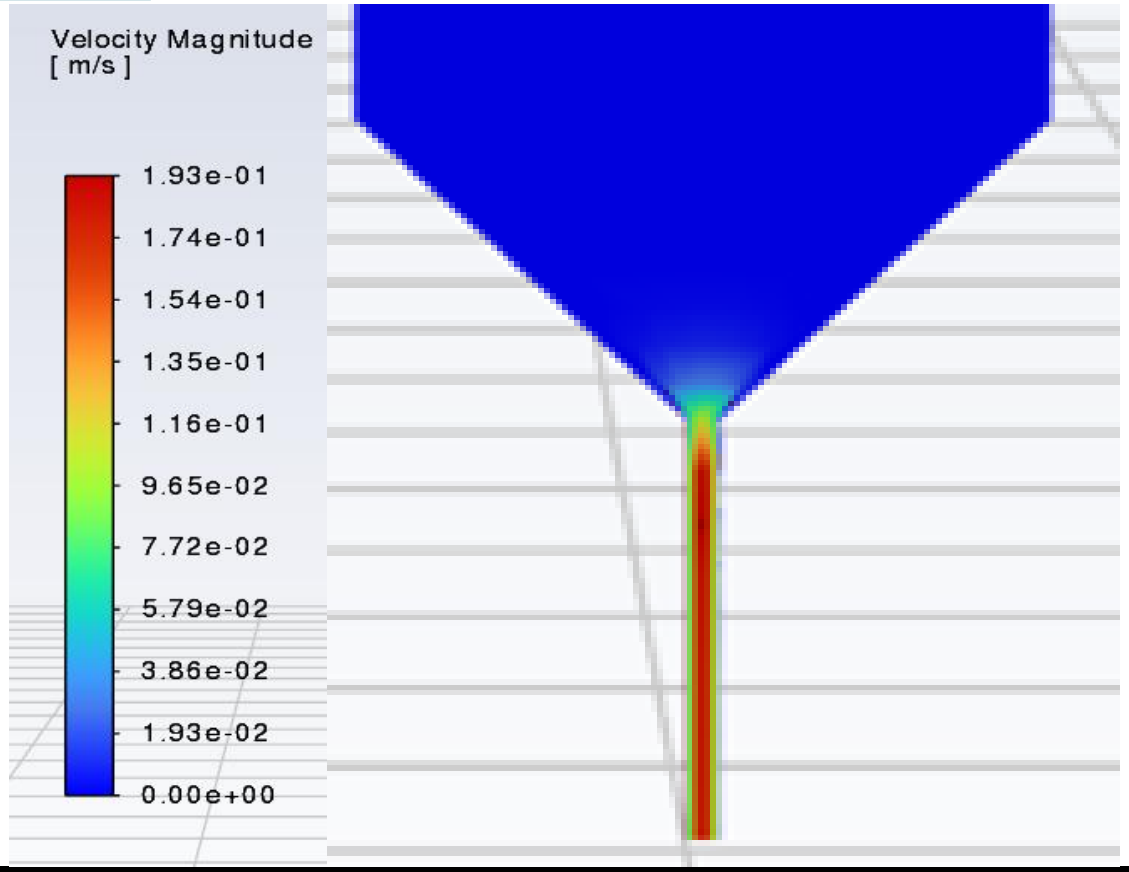
Mass flow rate:
0.0002 kg/s

Velocity In:
0.00025 m/s

Earth-based



Psyche-based

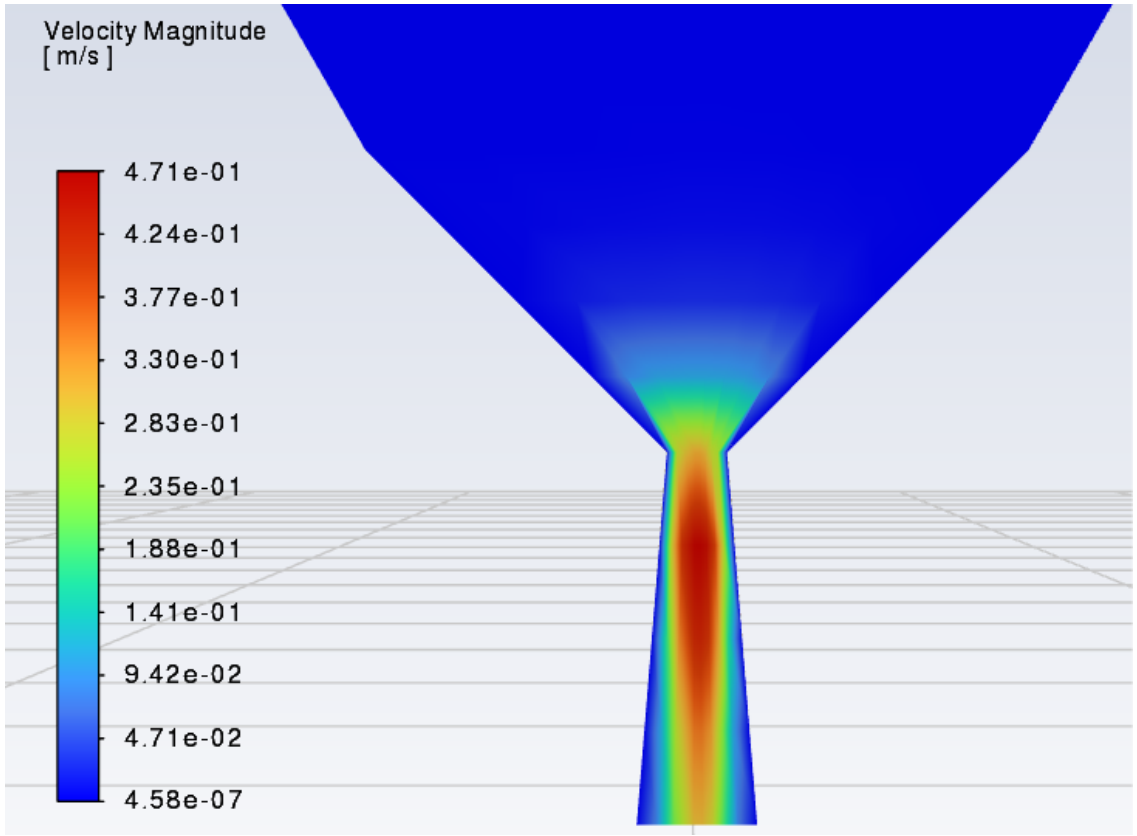


Results → Flow

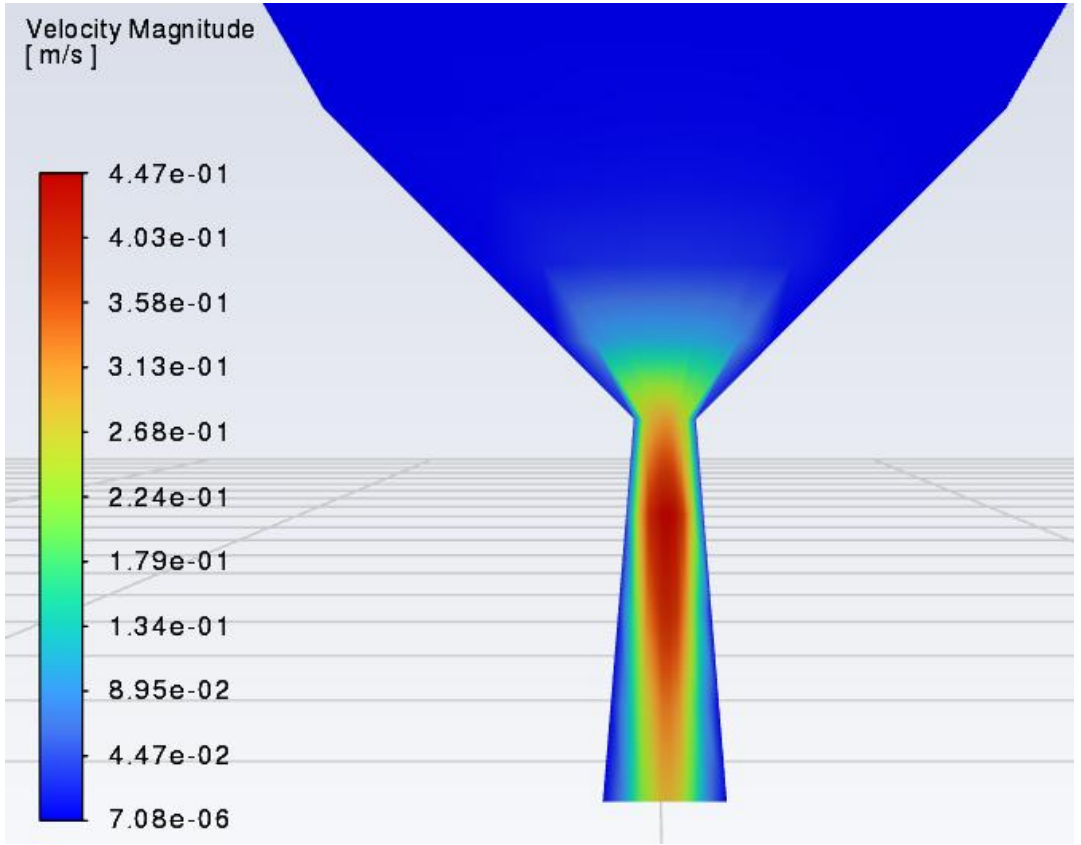
Mass flow rate:
0.0008 kg/s

Velocity In:
0.001 m/s

Earth-based



Psyche-based

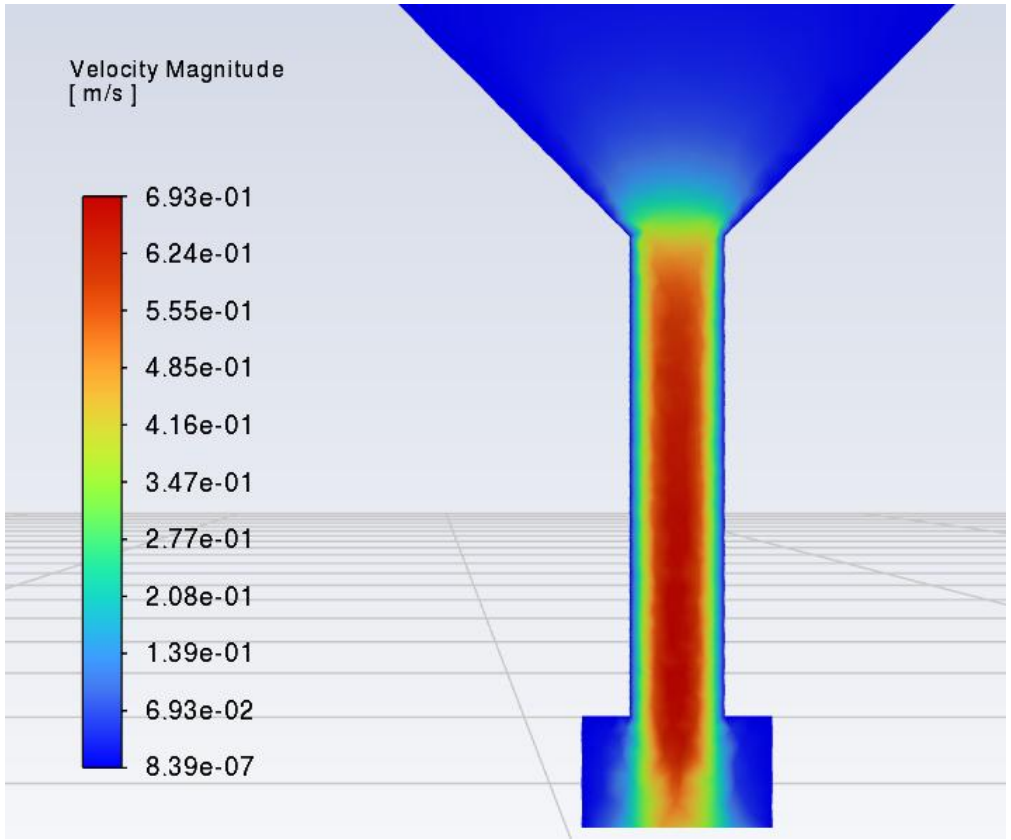


Results → Flow

Mass flow rate:
0.0008 kg/s

Velocity In:
0.001 m/s

Earth-based

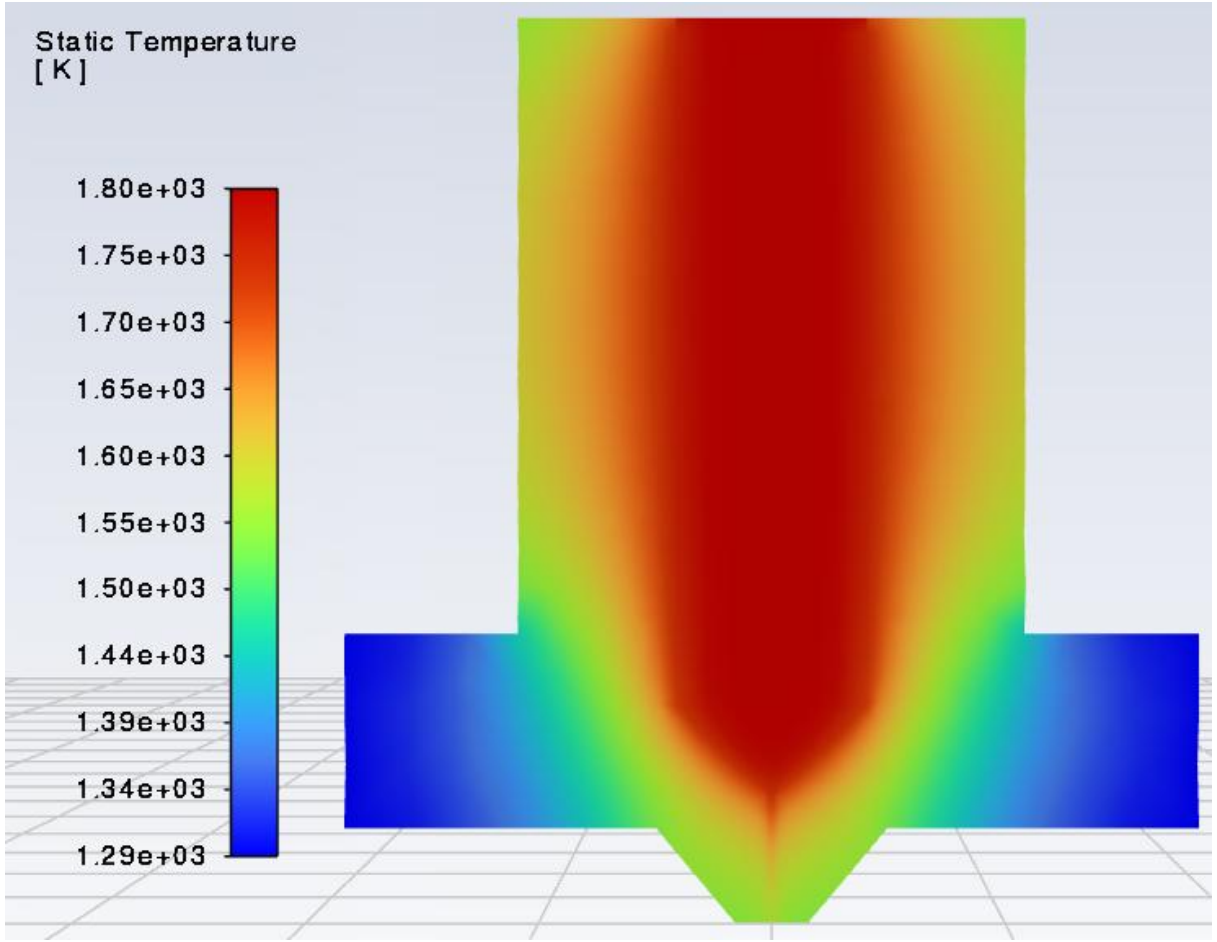


Psyche-based

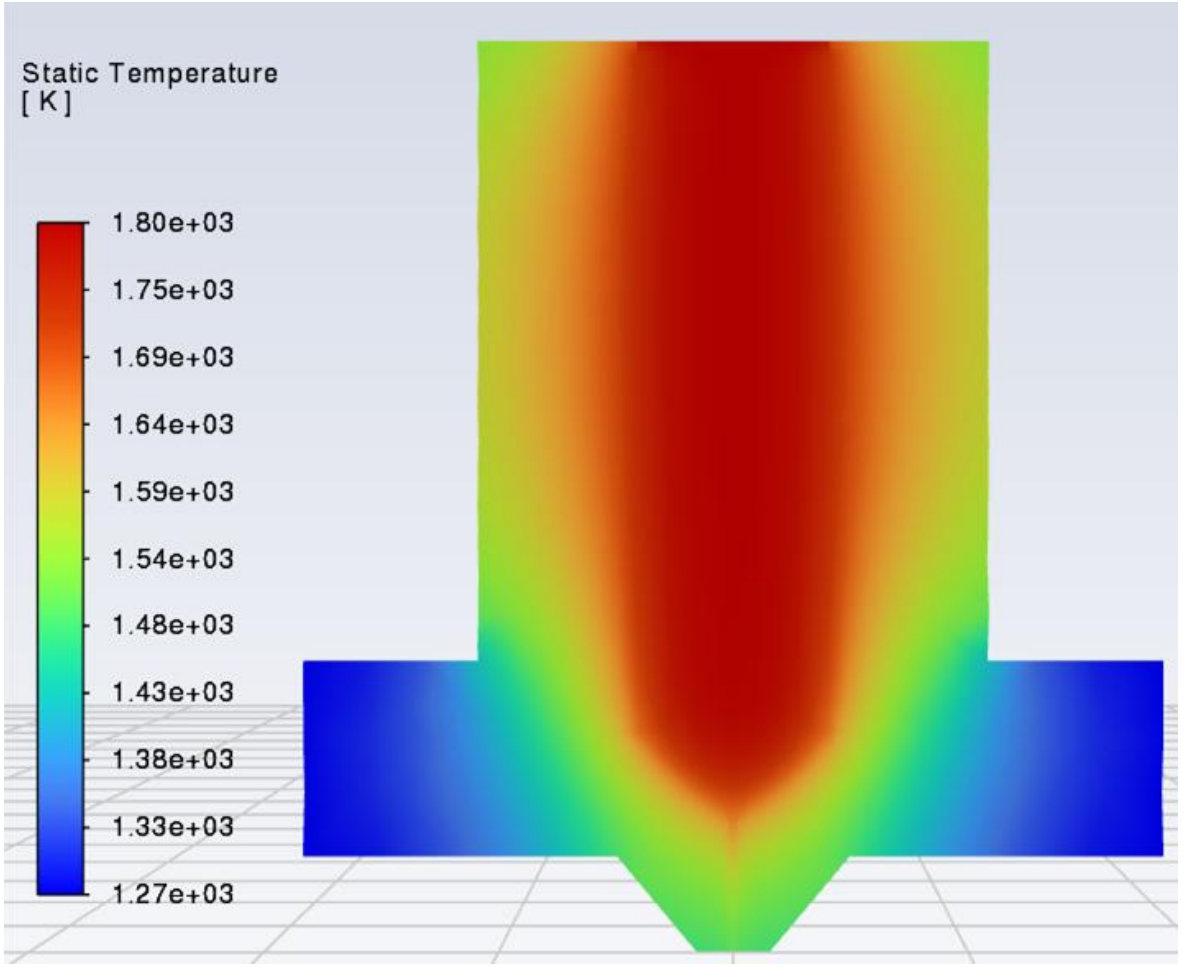
FAILED

Results → Thermal

Earth-based

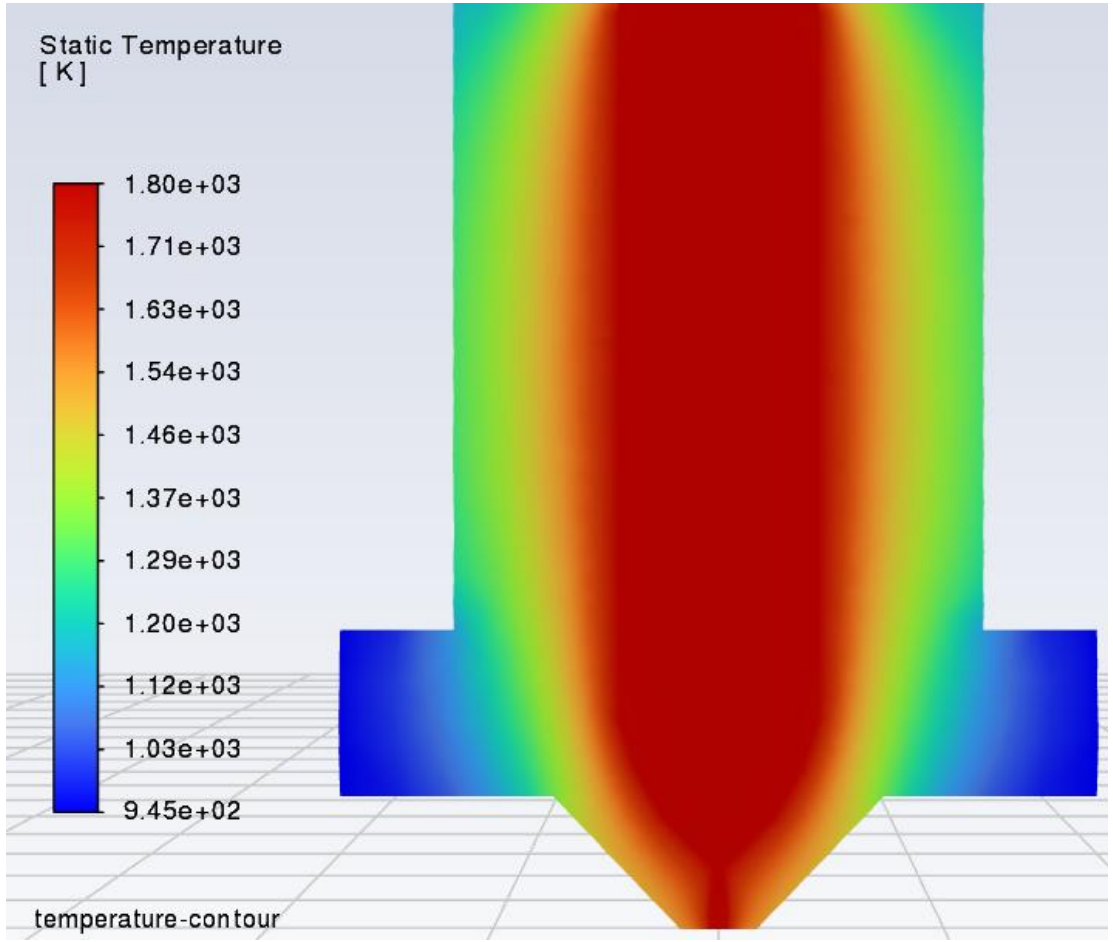


Psyche-based

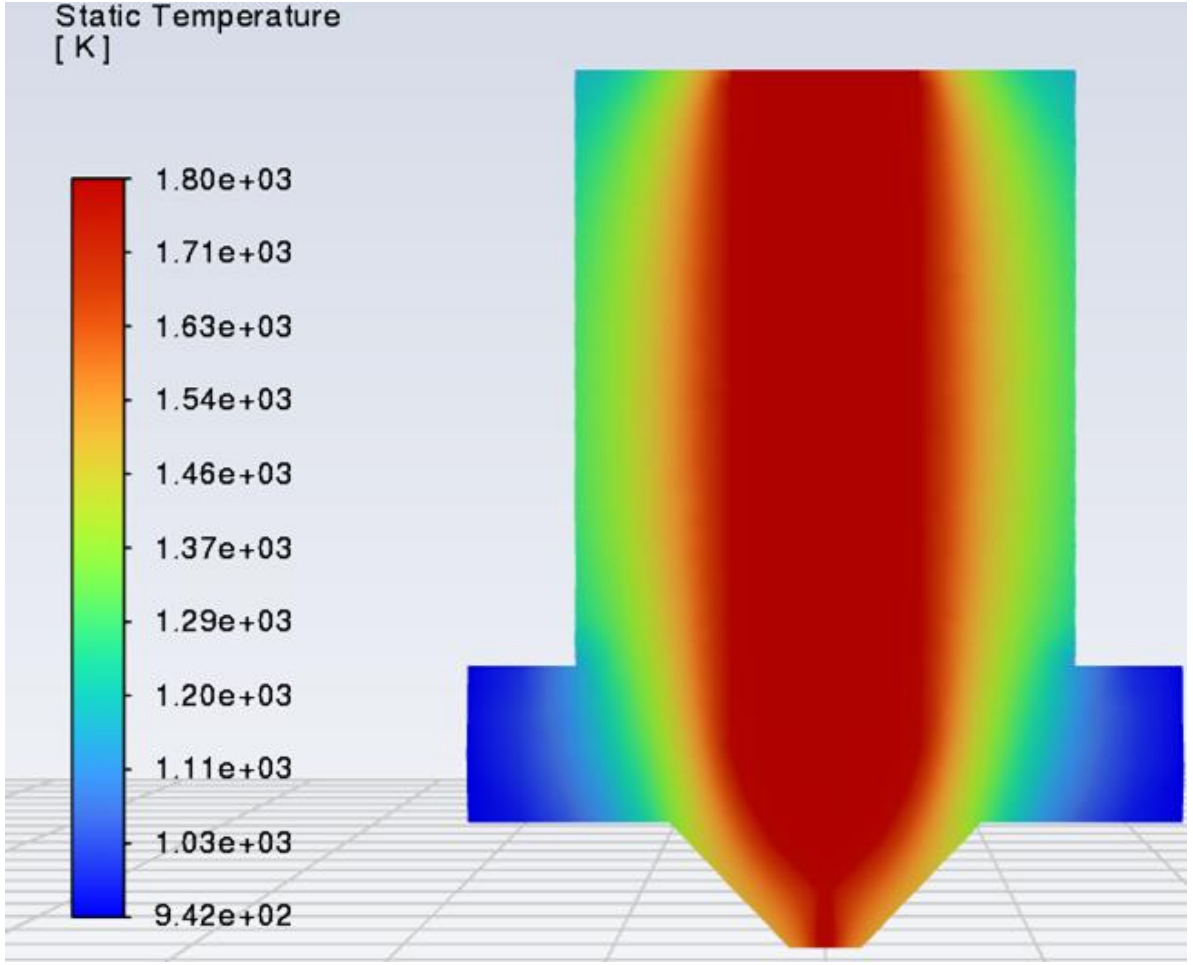


Results → Thermal

Earth-based

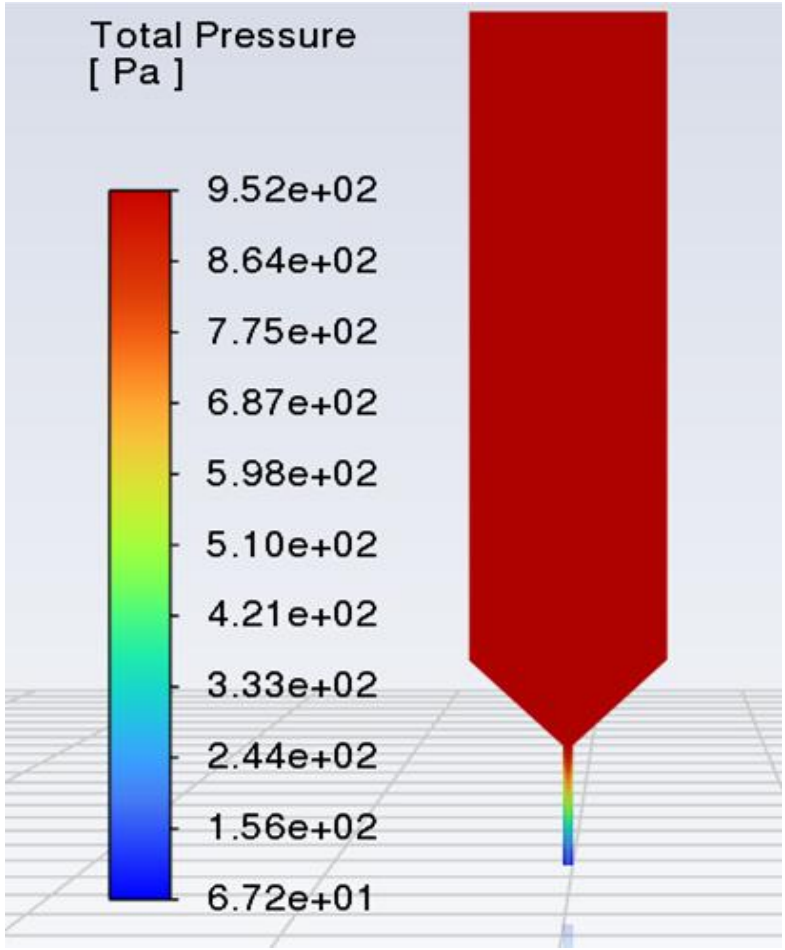


Psyche-based

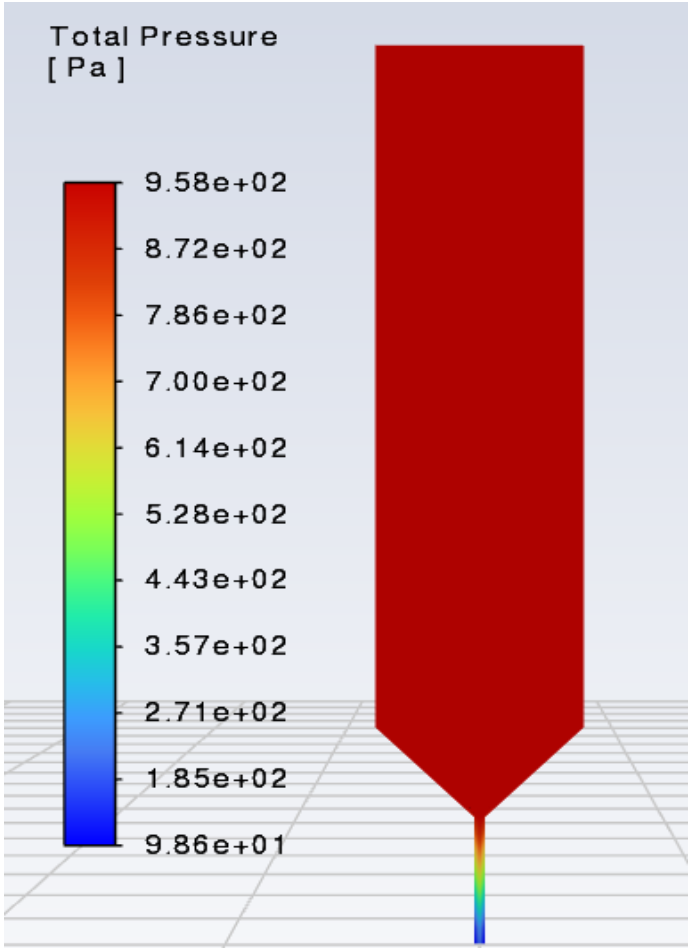


Results → Pressure

Earth-based

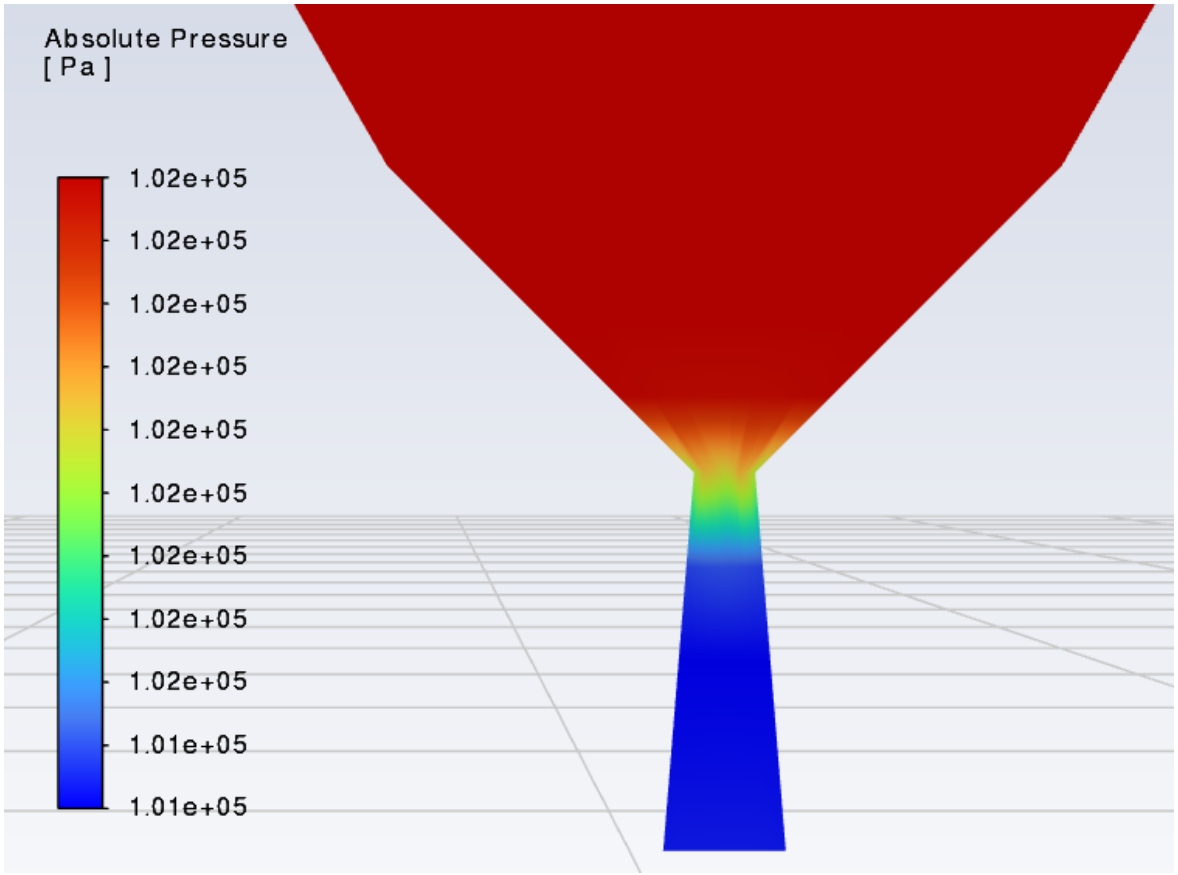


Psyche-based

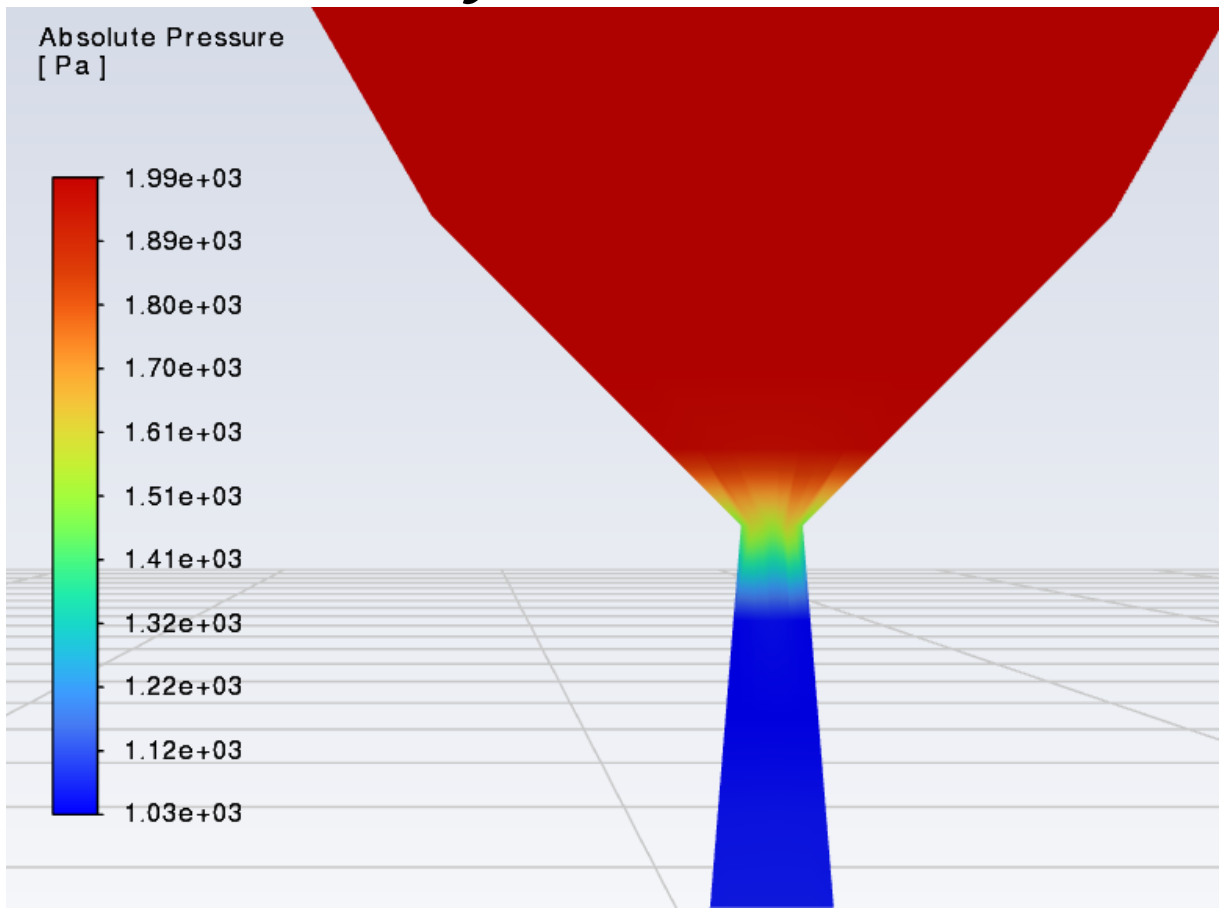


Results → Pressure

Earth-based



Psyche-based

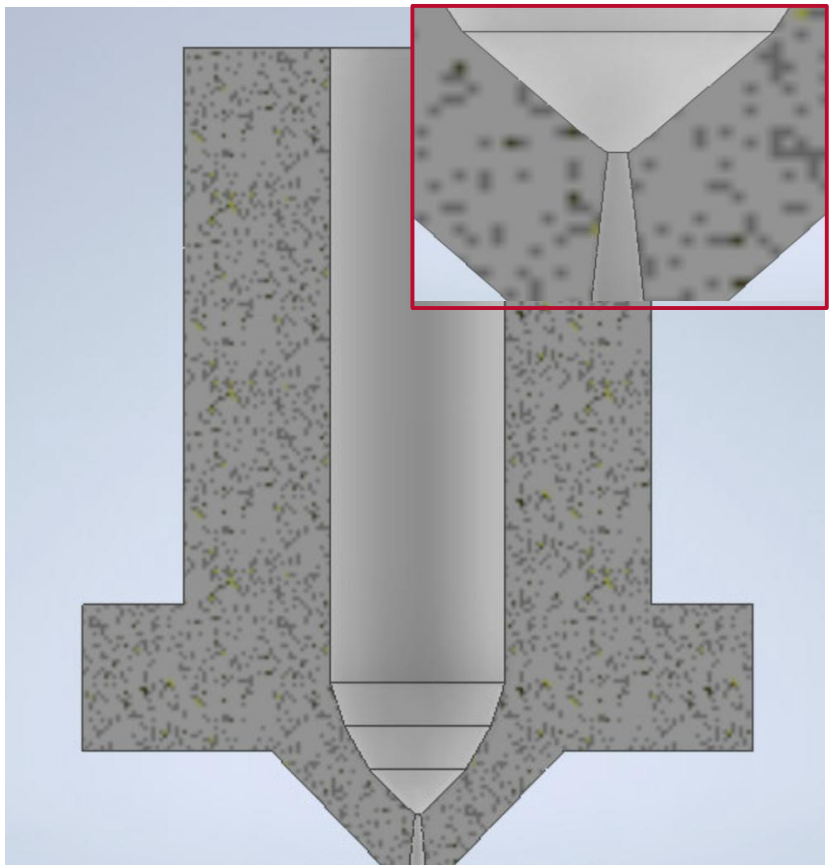


Simulation Analysis

Nozzle Geometry of Choice: Diverging Nozzle

1. **Die Swell Mitigation**
   - A divergent section at the end of nozzle acts as relaxation zone
2. **Fiber Orientation Control**
   - Has transverse flow component to align fibers
   - Increases cross-path strength
3. **Surface Ironing**
   - Smoothes out top layer as it's deposited
   - Helps with inter-layer adhesion

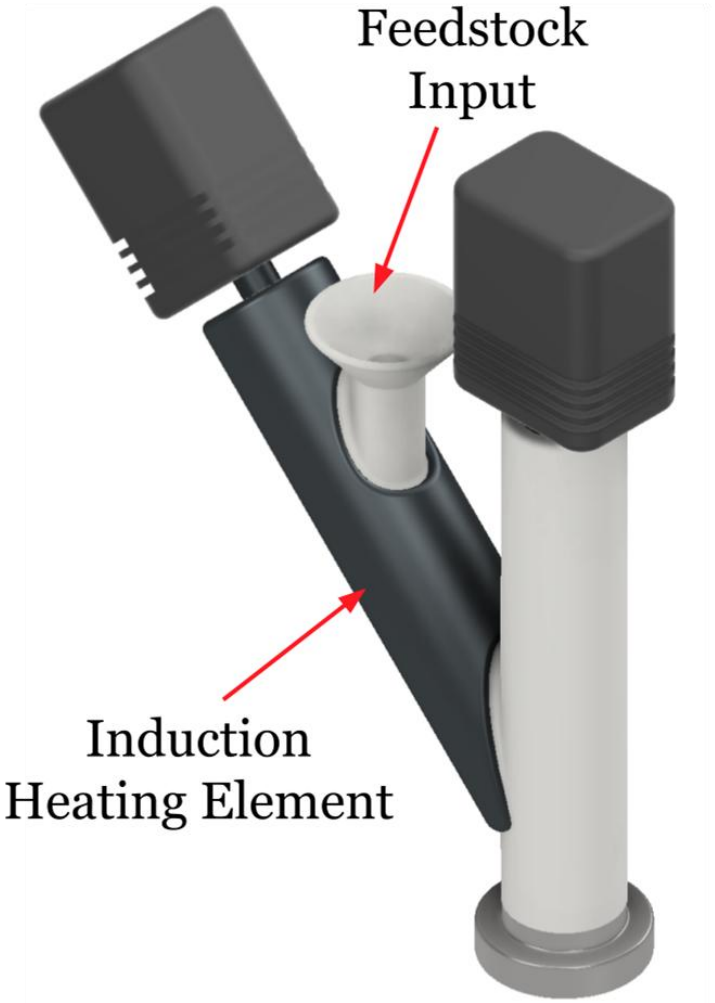
Converging-Diverging

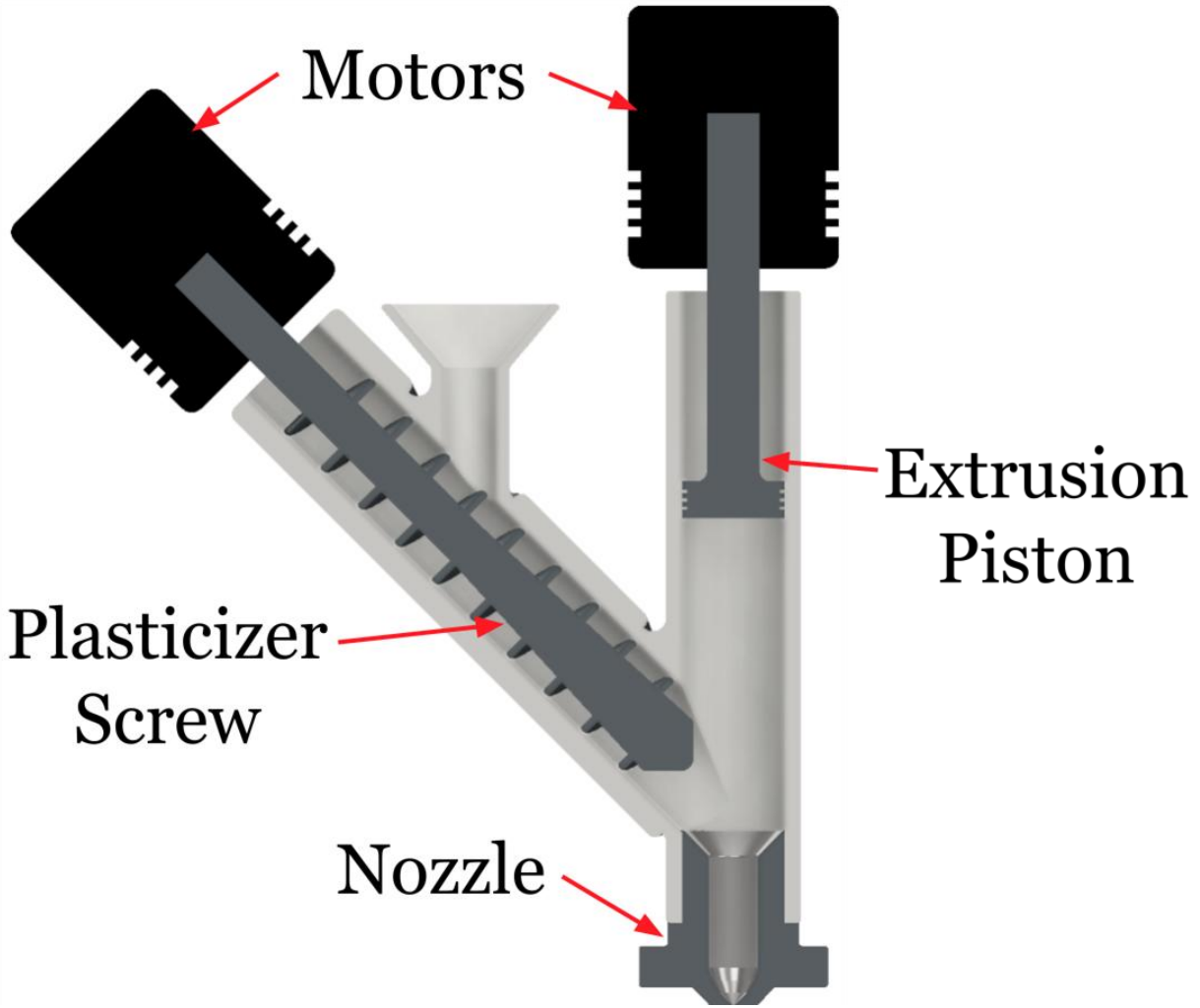


CAD Modeling

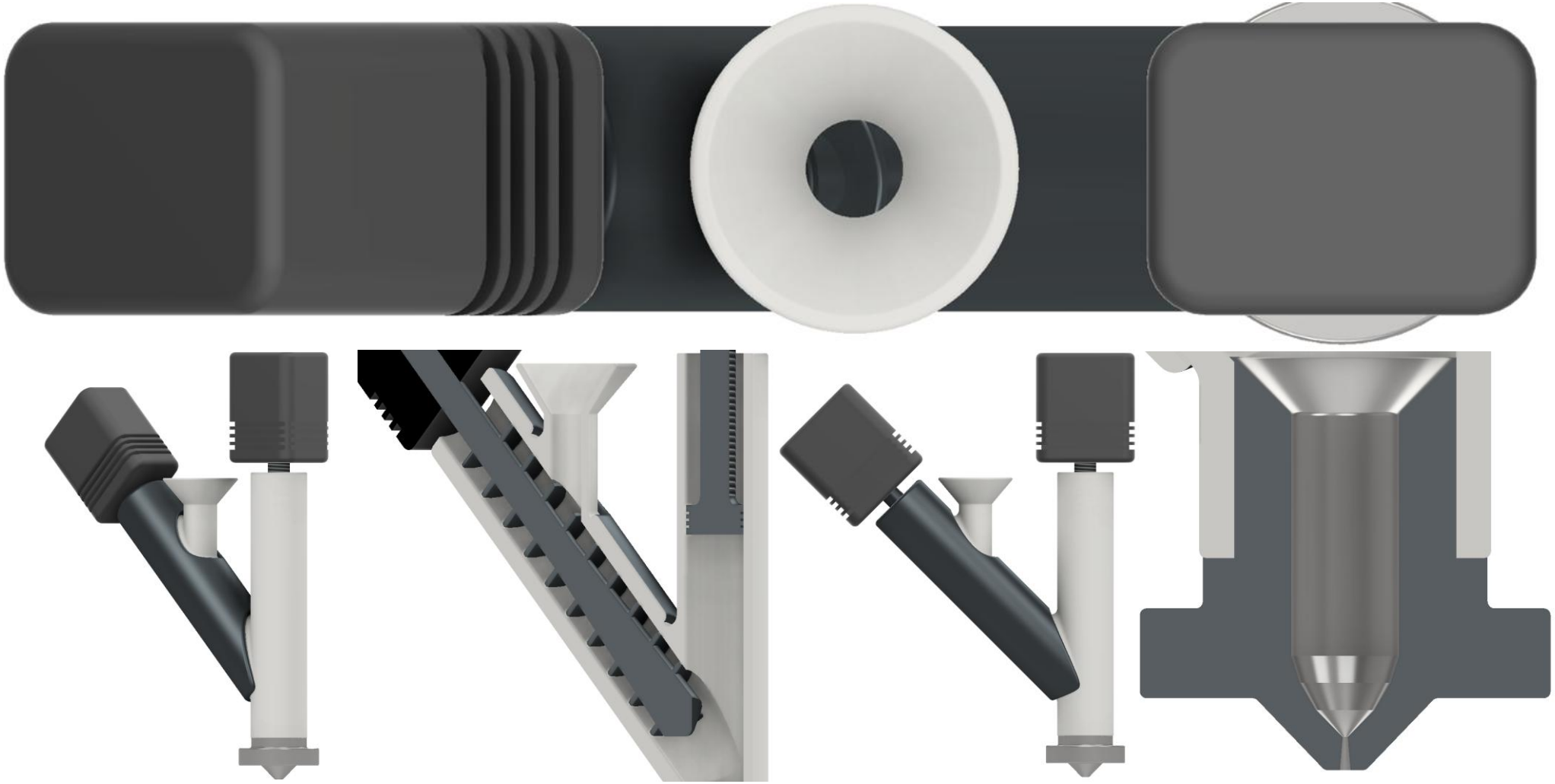
Proposed Extrusion Mechanism

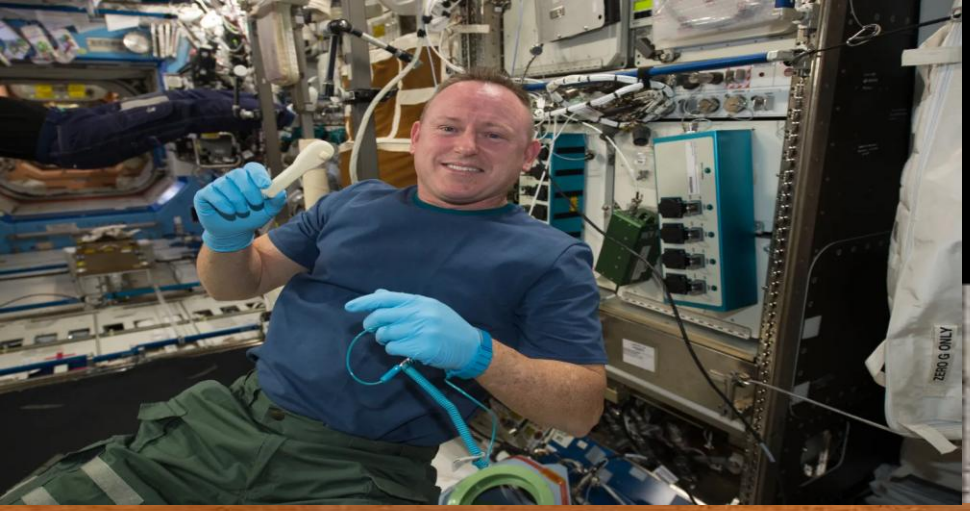
Proposed Extrusion Mechanism

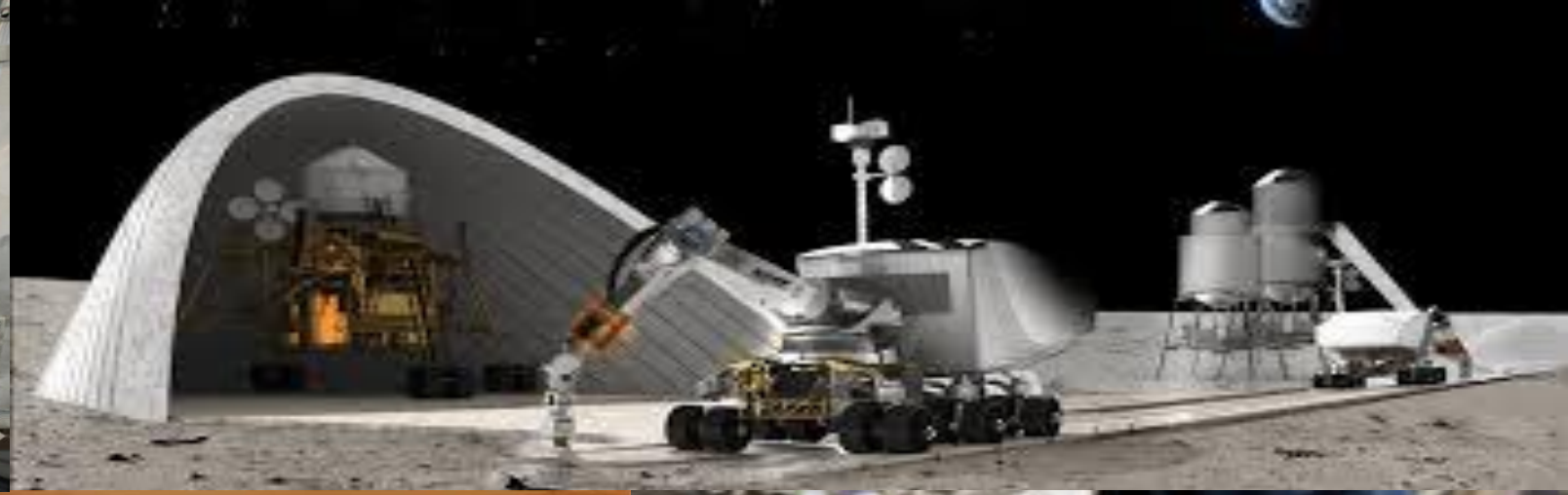




Proposed Extrusion Mechanism







CONCLUSION

Summary and Future Works

UNIVERSITY OF GEORGIA

Executive Summary

- ★ This project investigates the feasibility of adapting fused deposition modeling (FDM) for metal additive manufacturing on asteroid 16 Psyche.
- ★ Environmental challenges such as vacuum conditions, extreme temperatures, and low gravity significantly influence extrusion behavior and system design.
- ★ Verification plans focus on comparing simulation results with theoretical models to assess functionality, sustainability, and safety.
- ★ CFD and thermal simulations were developed to analyze nozzle performance, mass flow rate, and pressure and temperature gradients.
- ★ Initial results highlight key risks including thermal shock, pressure drops, and potential nozzle clogging under Psyche-like conditions.
- ★ Future work will refine material properties, optimize nozzle geometries, and deliver a feasibility analysis for in-situ resource utilization, with design revisions accompanying new data collected on Psyche.

Future Works

- Additional research on material/environmental composition of Psyche
- Validation of simulation results through experimental testing in low-gravity and vacuum-like conditions
- Further optimization of all aspects of the adapted FDM system
- Exploration into other AM methods on Psyche