



Building Amongst the Stars

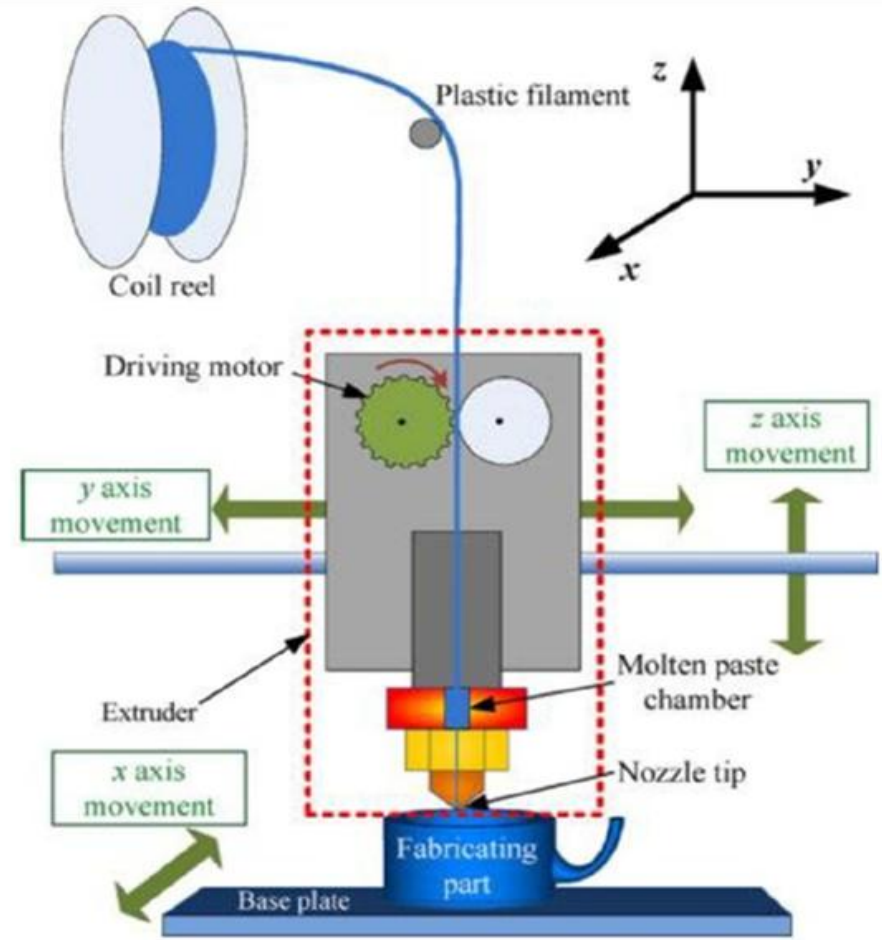
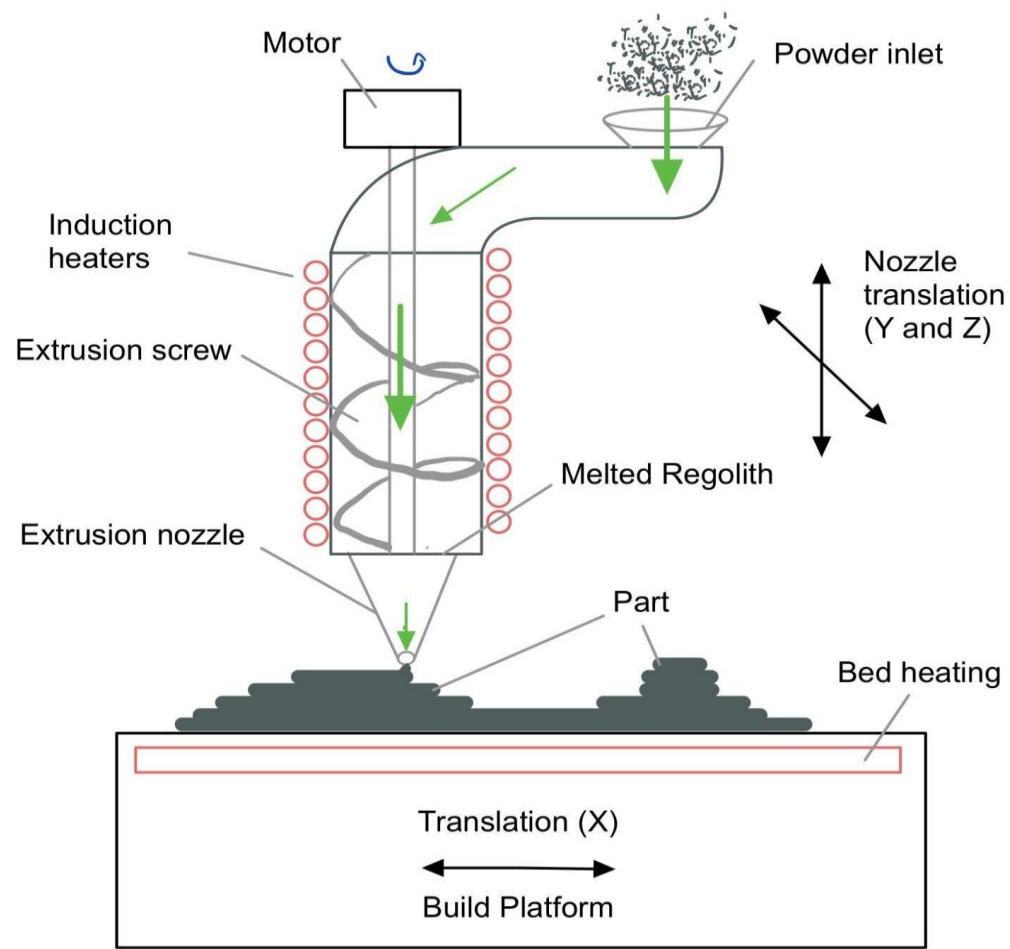
F25 – NP – Design and Analysis of Extrusion Mechanics for an Adapted Fused Deposition Modeling System on Asteroid 16–Psyche

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2025–2026 Capstone Design (MCHE 4910/4911)



College of Engineering
UNIVERSITY OF GEORGIA



EXPERIMENTAL DESIGN

Evaluation Criteria, Simulation, and Analysis

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)



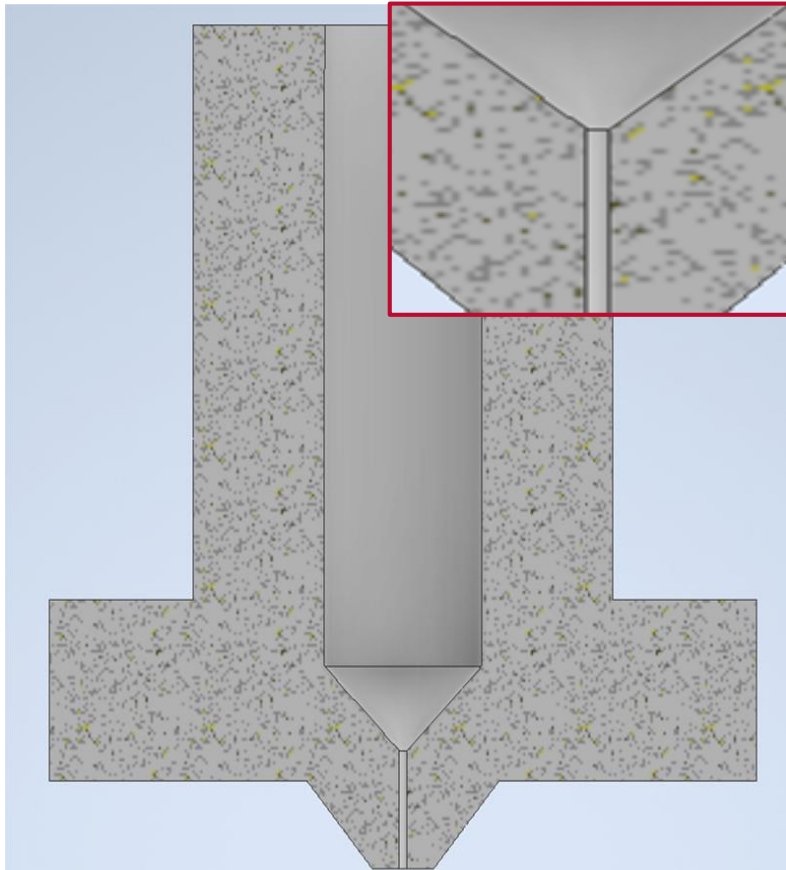
ANSYS Simulation

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

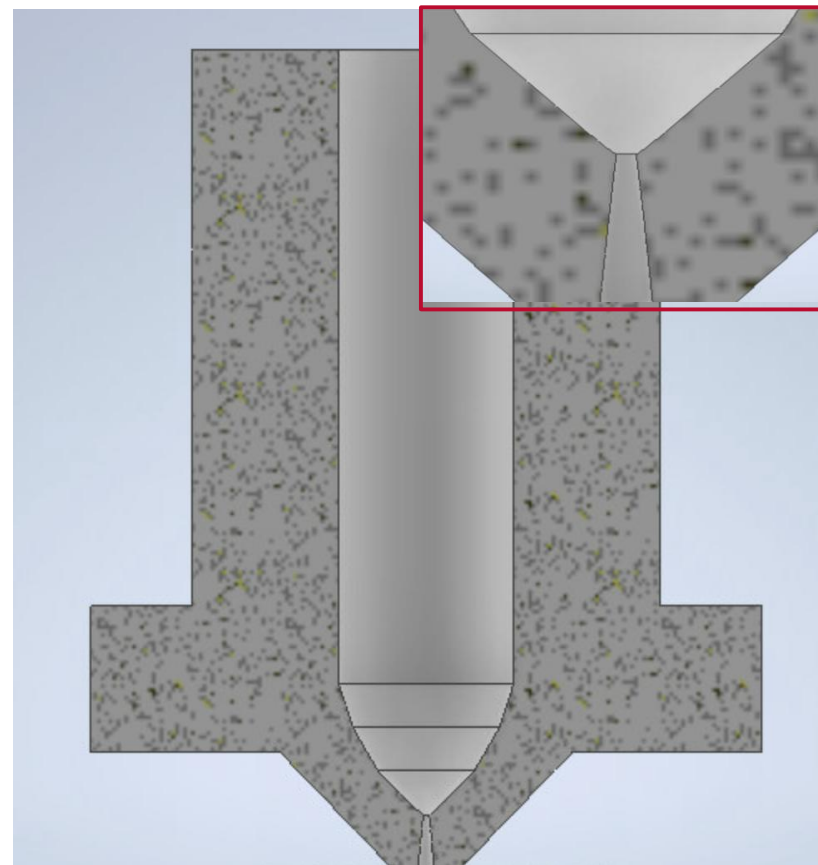


Simulation Set Up → Geometries

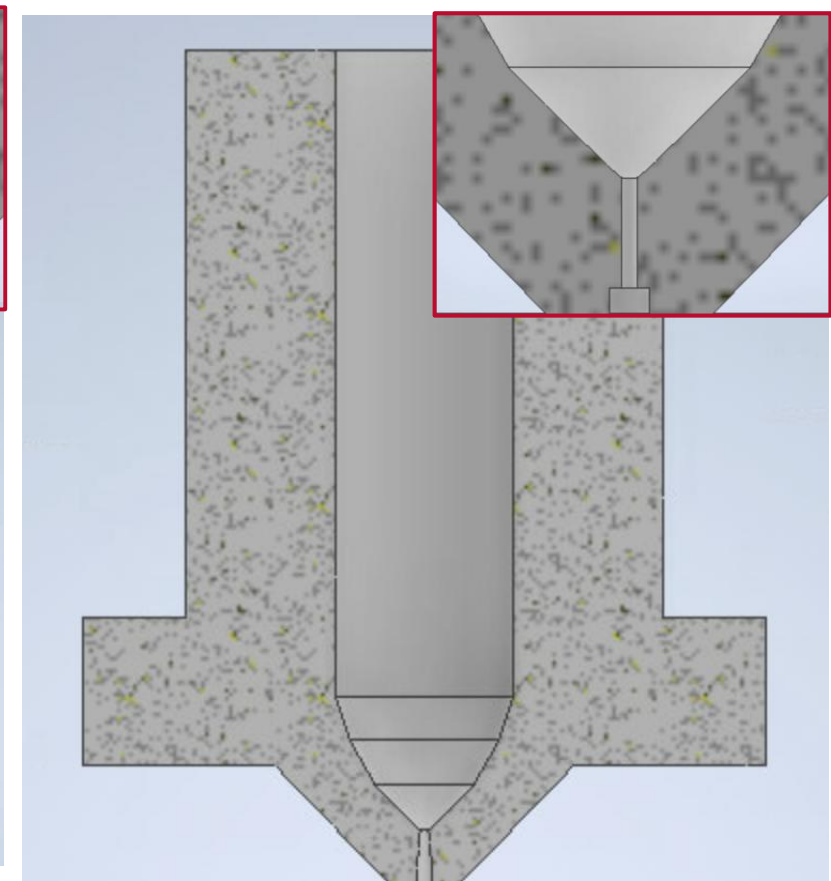
Converging



Converging-Diverging



Converging-Stepped



Simulation Set Up → System Setting

Earth-based

Operating Conditions

Pressure

Operating Pressure [Pa]
101325

Reference Pressure Location

X [mm] 0

Y [mm] 0

Z [mm] 0

Gravity

Gravity

Gravitational Acceleration

X [m/s²] 0

Y [m/s²] -9.81

Z [m/s²] 0

Boussinesq Parameters

Operating Temperature [K]
300

Psyche-based

Operating Conditions

Pressure

Operating Pressure [Pa]
0

Reference Pressure Location

X [mm] 0

Y [mm] 0

Z [mm] 0

Gravity

Gravity

Gravitational Acceleration

X [m/s²] 0

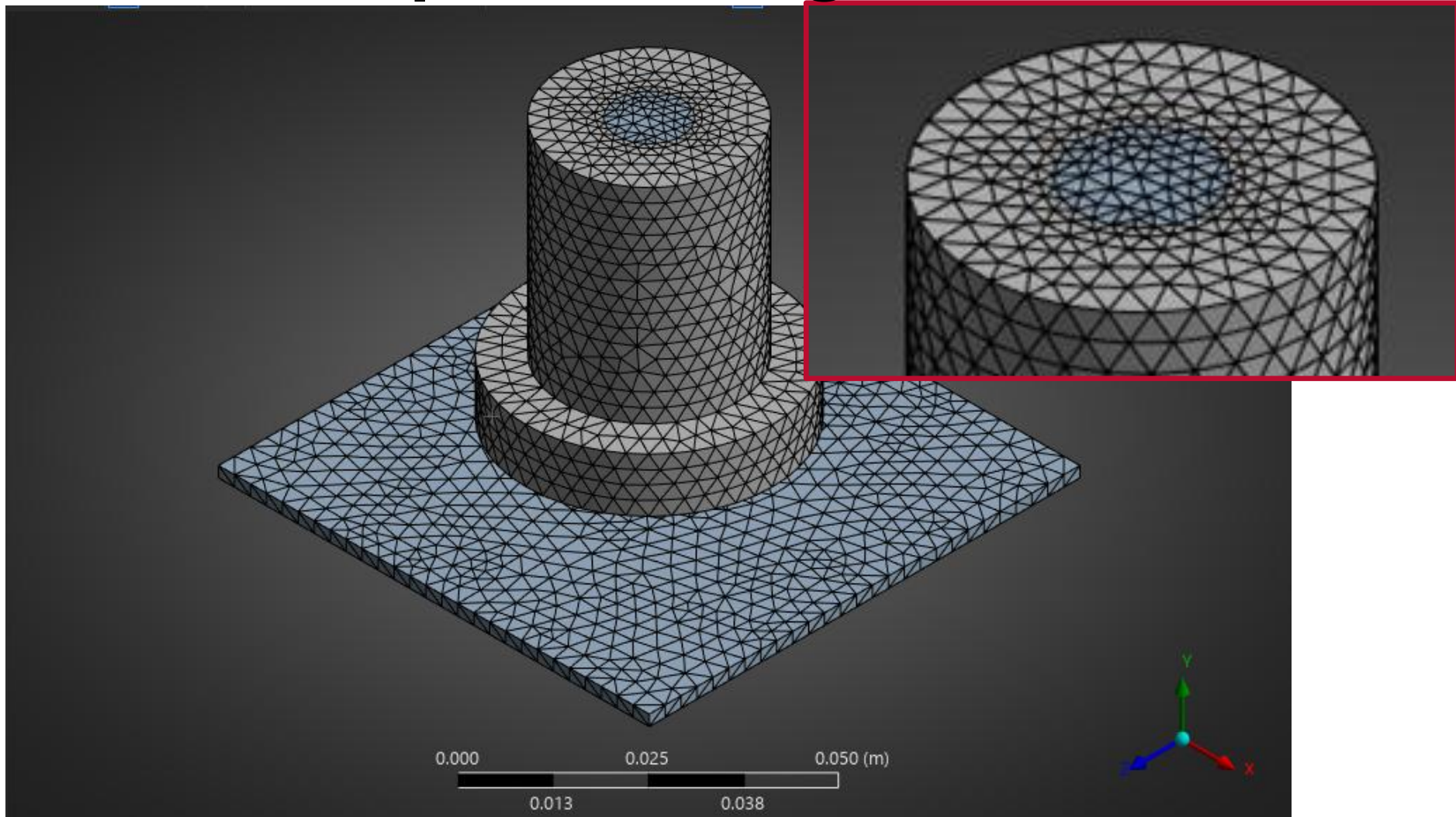
Y [m/s²] -0.144

Z [m/s²] 0

Boussinesq Parameters

Operating Temperature [K]
200

Simulation Set Up → Meshing



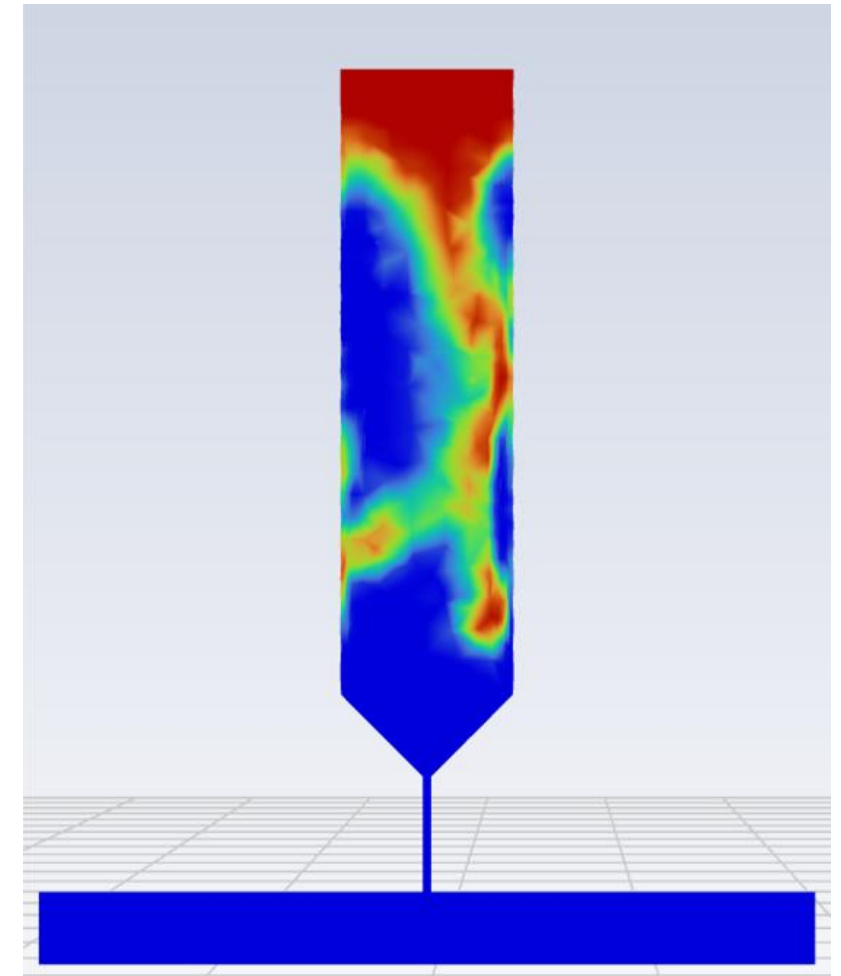
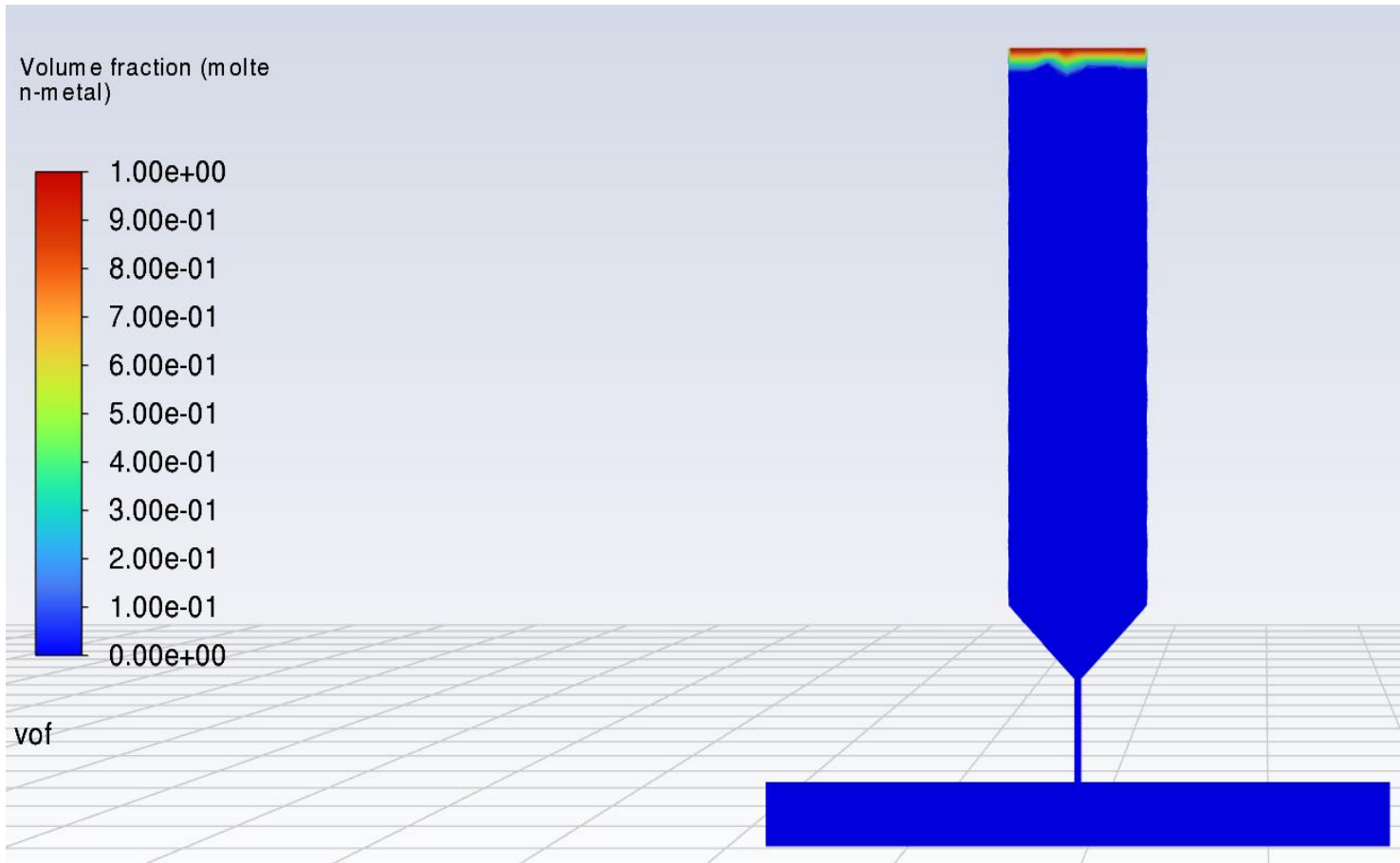
Simulation Set Up → Meshing

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

<input checked="" type="checkbox"/> Sheet <input checked="" type="checkbox"/> Solid <input checked="" type="checkbox"/> Solid - Surface				
Error Check	Quality Criterion	Warning Limit	Error (Failure) Limit	Worst
<input type="checkbox"/>	Max Aspect Ratio	Default (5)	Default (1000)	3.129
<input type="checkbox"/>	Max Tri Angle	Default (160 °)	Default (170 °)	118.905 °
<input type="checkbox"/>	Min Element Edge Length	Default (6.4e-04 m)	Default (6.4e-05 m)	1e-04 m
<input type="checkbox"/>	Min Tri Angle	Default (20 °)	Default (10 °)	20.524 °
<input type="checkbox"/>	Max Skewness	Default (0.9)	Default (0.999)	0.692



Simulation Enhancements → Viscosity Modeling



Failed Viscosity Model

Simulation Enhancements → Viscosity Modeling

Viscous Model

Model

- Inviscid
- Laminar
- Spalart-Allmaras (1 eqn)
- k-epsilon (2 eqn)
- k-omega (2 eqn)
- Transition k-k1-omega (3 eqn)
- Transition SST (4 eqn)
- Reynolds Stress (7 eqn)
- Scale-Adaptive Simulation (SAS)
- Detached Eddy Simulation (DES)
- Large Eddy Simulation (LES)

Options

- Viscous Heating
- Low-Pressure Boundary Slip

OK Cancel Help

```
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

Create/Edit Materials

Name: molten-metal

Material Type: fluid

Chemical Formula:

Fluent Fluid Materials: molten-metal

Mixture: none

Order Materials by:
 Name
 Chemical Formula

Fluent Database...
GRANTA MDS Database...
User-Defined Database...

Properties

Density [kg/m³]: constant (Edit...)
7250

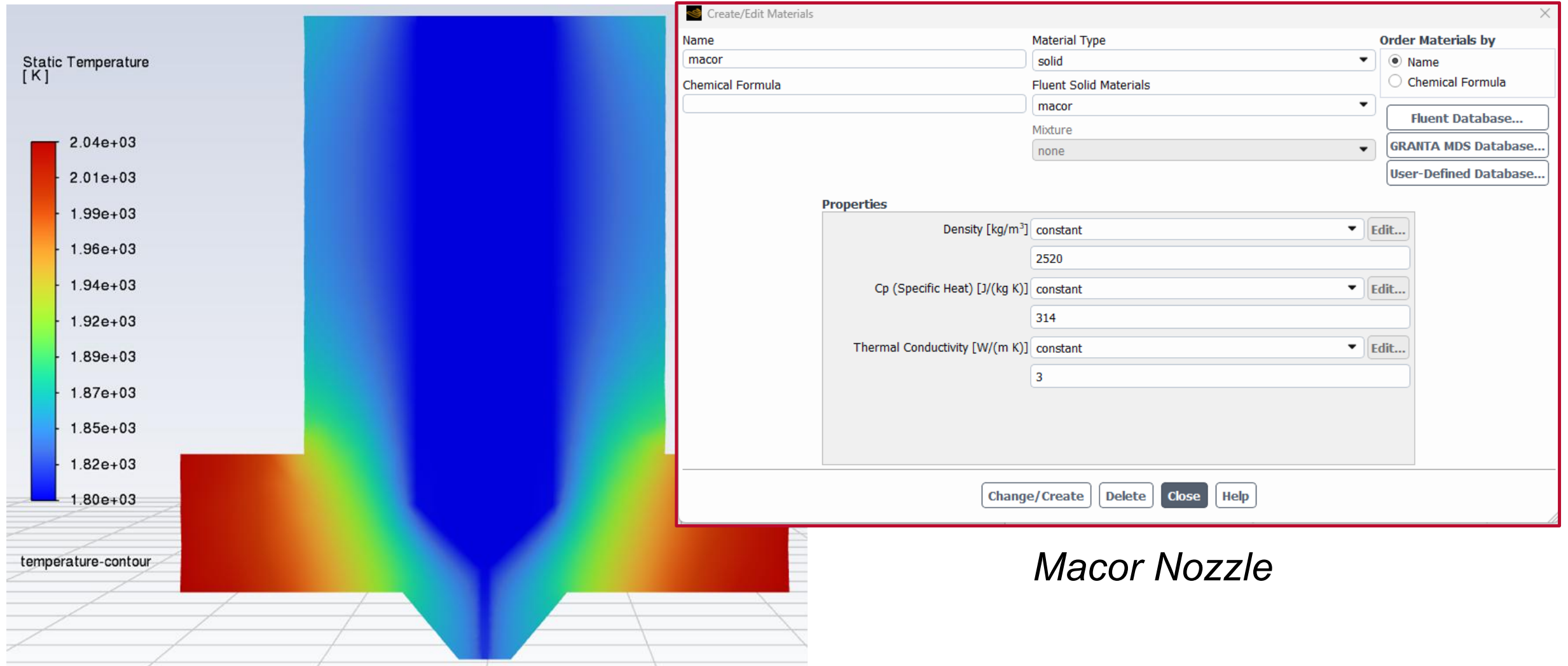
Cp (Specific Heat) [J/(kg K)]: constant (Edit...)
500

Thermal Conductivity [W/(m K)]: constant (Edit...)
30

Viscosity [kg/(m s)]: user-defined (Edit...)
viscosity_fe30ni::libudf

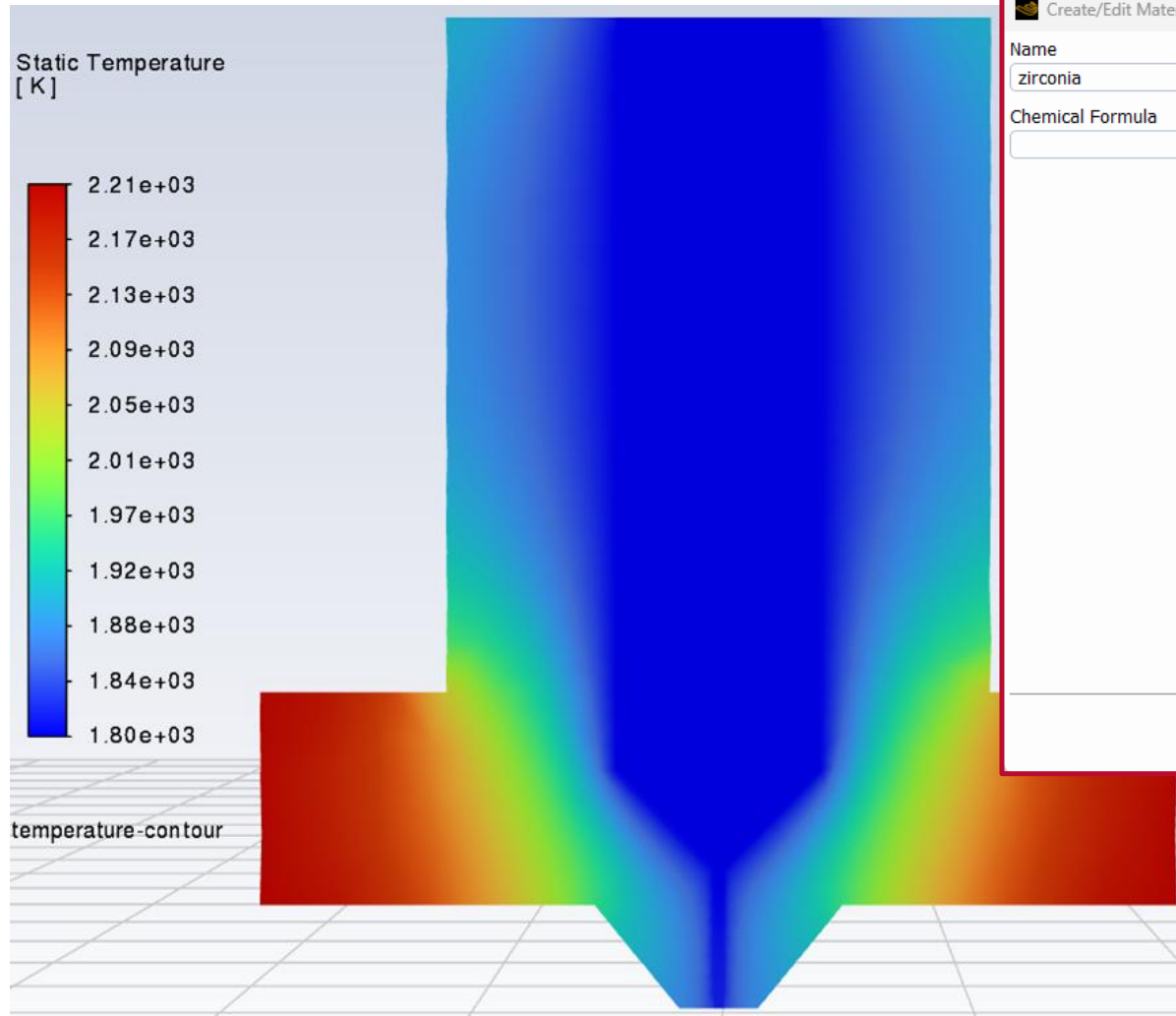
Change/Create Delete Close Help

Simulation Enhancements → Properties



Macor Nozzle

Simulation Enhancements → Properties



Create/Edit Materials

Name: zirconia

Material Type: solid

Chemical Formula:

Fluent Solid Materials: zirconia

Mixture: none

Order Materials by: Name Chemical Formula

Fluent Database...
GRANTA MDS Database...
User-Defined Database...

Properties

Density [kg/m³]: constant (6100) Edit...

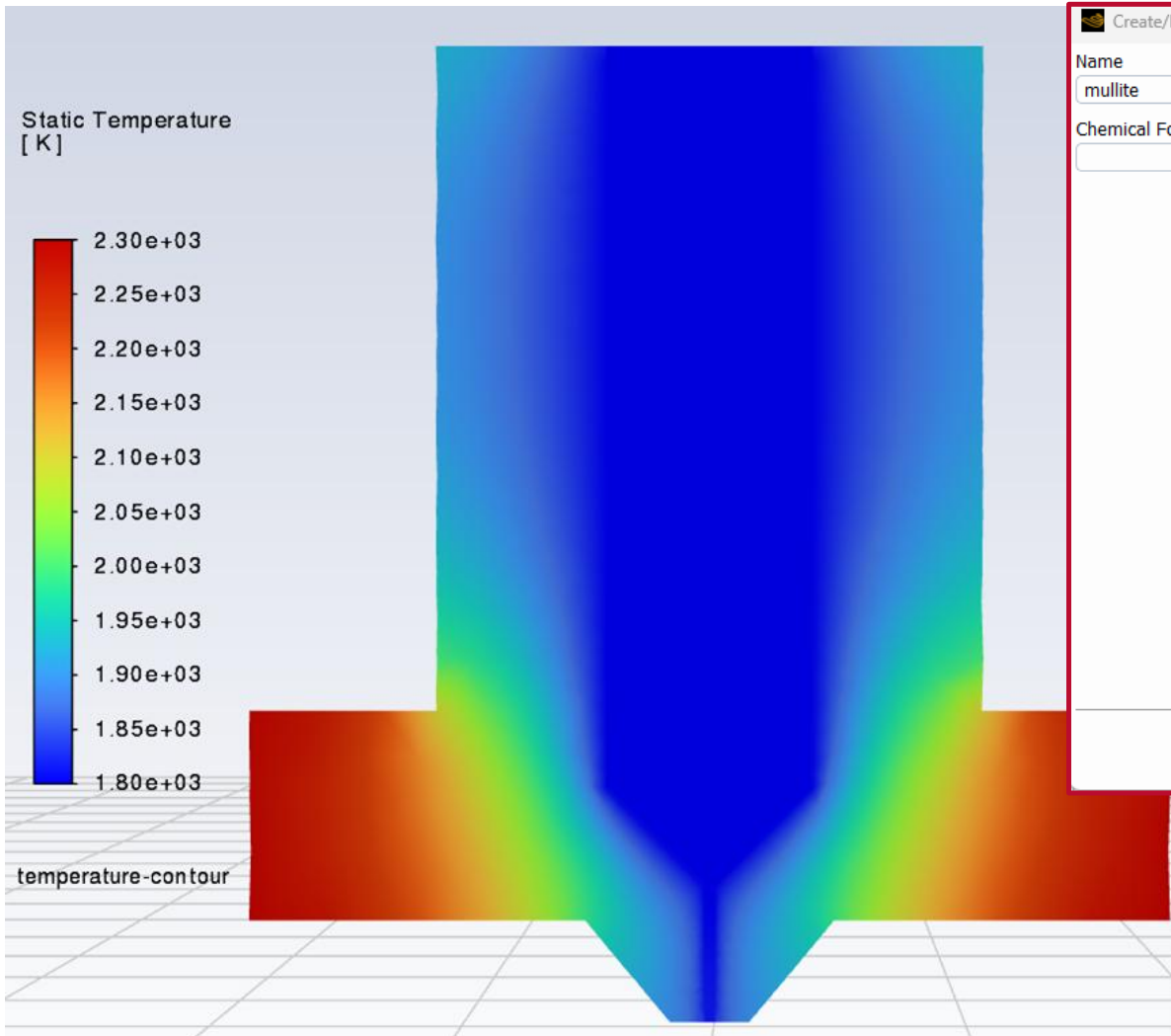
Cp (Specific Heat) [J/(kg K)]: constant (420) Edit...

Thermal Conductivity [W/(m K)]: constant (1.7) Edit...

Change/Create Delete Close Help

Zirconia Nozzle

Simulation Enhancements → Properties



Create/Edit Materials

Name: mullite

Material Type: solid

Chemical Formula:

Fluent Solid Materials: mullite

Mixture: none

Order Materials by: Name, Chemical Formula

Fluent Database...
GRANTA MDS Database...
User-Defined Database...

Properties

Density [kg/m³]: constant, 3160, Edit...

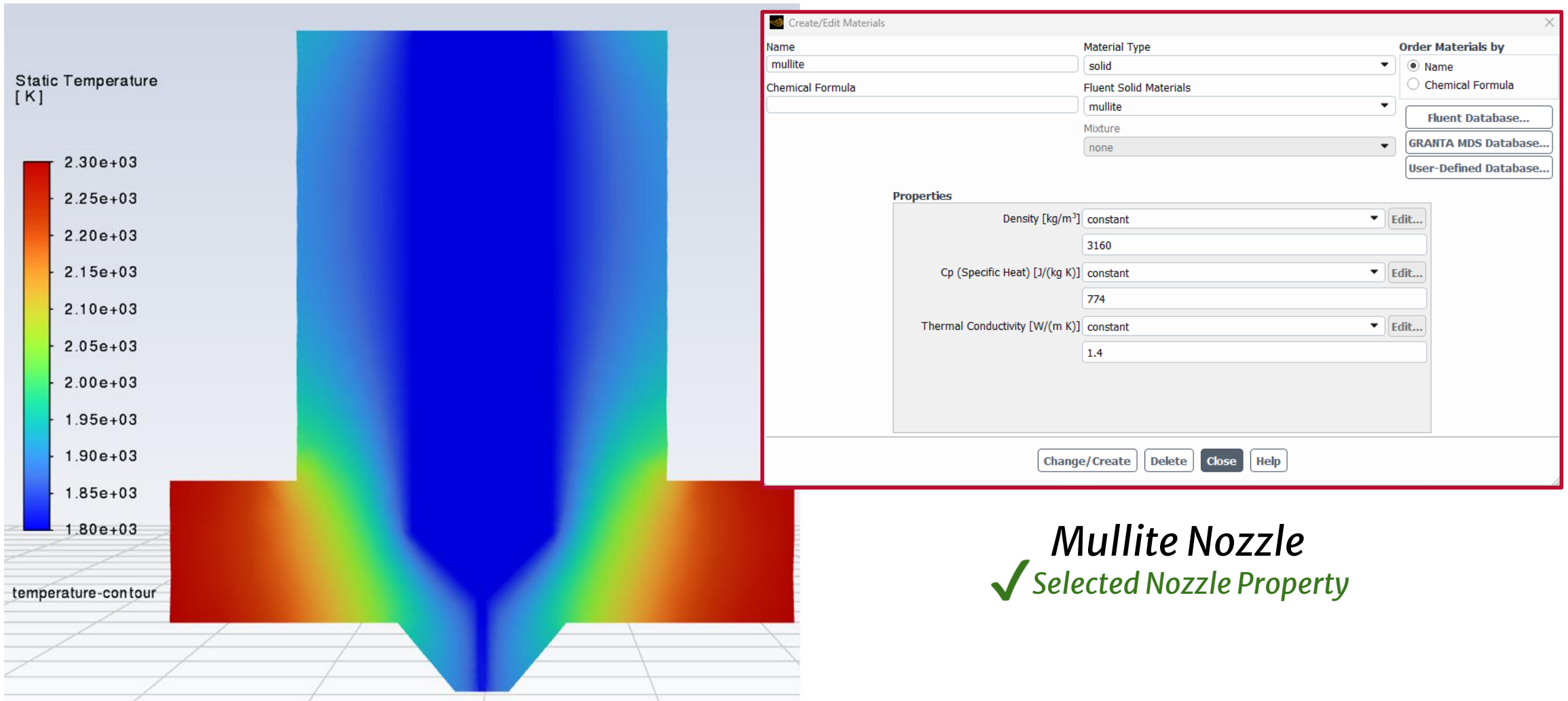
Cp (Specific Heat) [J/(kg K)]: constant, 774, Edit...

Thermal Conductivity [W/(m K)]: constant, 1.4, Edit...

Change/Create, Delete, Close, Help

Mullite Nozzle

Simulation Enhancements → Properties



✓ *Mullite Nozzle*
Selected Nozzle Property

Simulation Enhancements → Heating

The image shows a screenshot of the ANSYS Fluent software interface. On the left is the 'Wall' properties dialog, and on the right is the 'Expression Editor'.

Wall Properties Dialog:

- Zone Name: outer-nozzle-wall
- Adjacent Cell Zone: fff-nozzle
- Thermal Conditions:
 - Heat Flux:
 - Temperature:
 - Convection:
 - Radiation:
 - Mixed:
 - via System Coupling:
 - via Mapped Interface:
- Heat Transfer Coefficient [W/(m² K)]: 0
- Free Stream Temperature [K]: 300
- External Emissivity: 1
- External Radiation Temperature [K]: 300
- Wall Thickness [mm]: 10
- Heat Generation Rate: $[(0.0103[m]^2 - 0.0003 [m]^2) * 0.004 [m]]$ *fx*
- Shell Conduction: 1 Conduction Layer
- Material Name: mullite


Expression Editor:

```
25 [W] / ((PI*(0.016 [m]^2 - 0.006[m]^2) * 0.038[m]) + (PI/3 * 0.014 [m] * ((0.016 [m]^2 + 0.016 [m]*0.0103[m] + 0.0103[m]^2) - (0.006 [m]^2 + 0.006 [m]*0.010[m] + 0.010[m]^2)))) + (PI*(0.0103[m]^2 - 0.0003 [m]^2) * 0.004 [m]))
```

Current Value: Refresh value

Cannot plot expression: No independent variables found

Simulation Process

 Velocity Inlet ✕

Zone Name

Momentum Thermal Radiation Species DPM Multiphase Potential Structure UDS

Velocity Specification Method

Reference Frame

Velocity Magnitude [m/s]

Supersonic/Initial Gauge Pressure [Pa]

Simulation Process

Pressure Outlet

Zone Name
outlet

Momentum Thermal Radiation Species DPM Multiphase Potential Structure UDS

Gauge Pressure [Pa] 0

Pressure Profile Multiplier 1

Prevent Reverse Flow

Radial Equilibrium Pressure Distribution

Average Pressure Specification

Target Mass Flow Rate

Target Mass Flow [kg/s] 0.0002

Upper Limit of Absolute Pressure [Pa] 5000000

Lower Limit of Absolute Pressure [Pa] 1

Apply Close Help

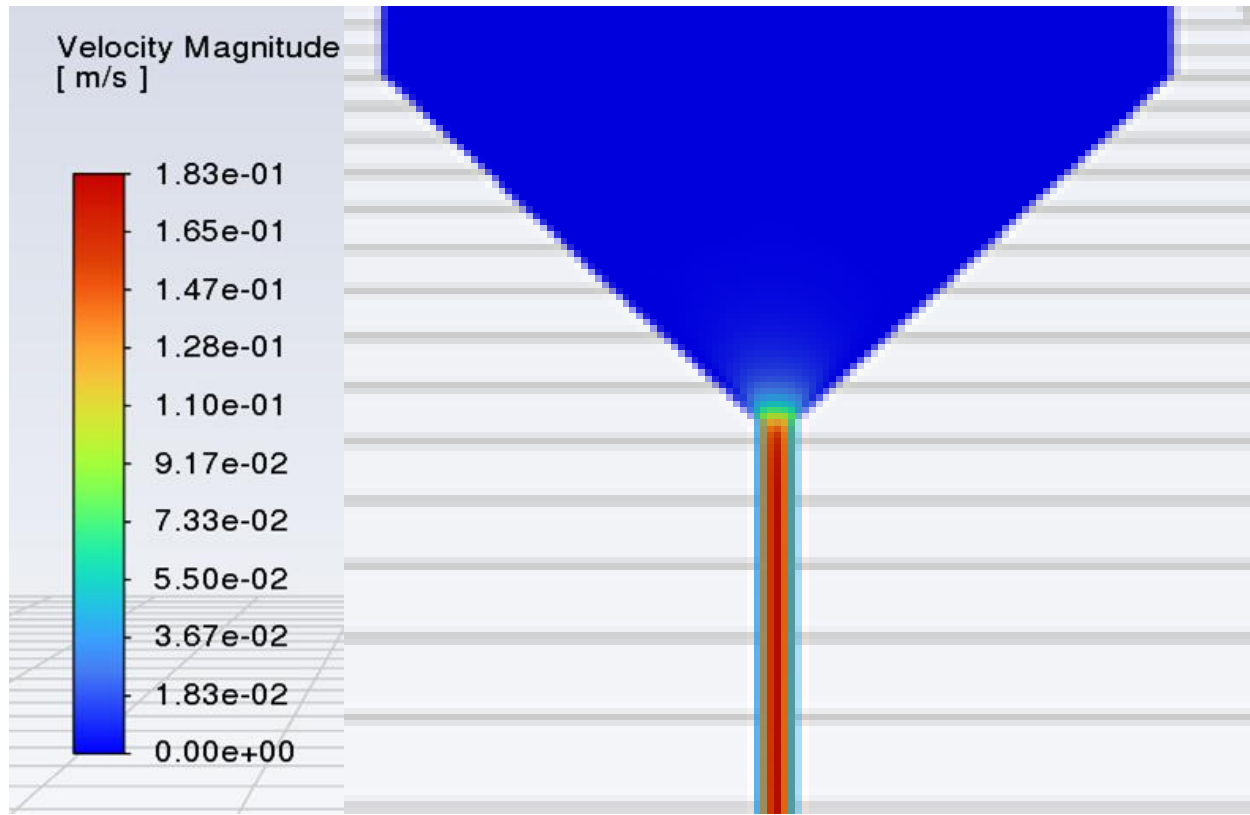


Results → Flow

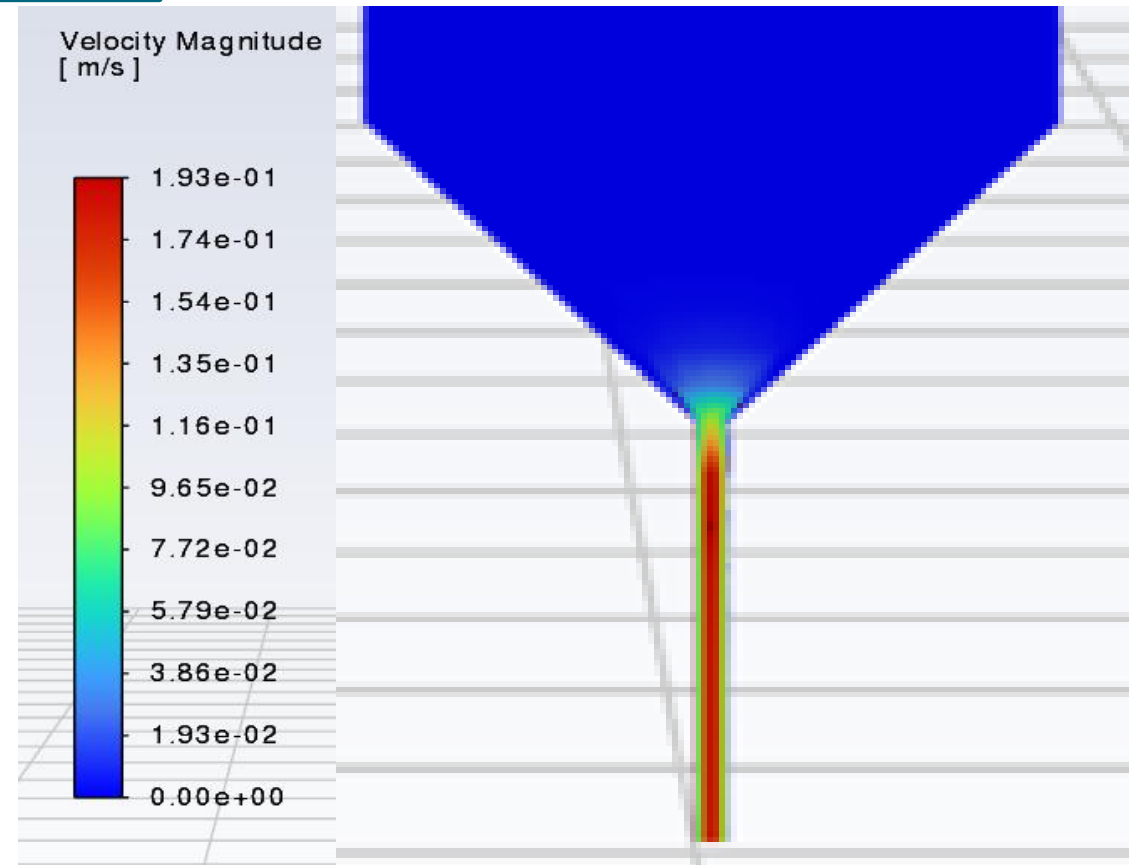
Mass flow rate:
0.0002 kg/s

Velocity In:
0.00025 m/s

Earth-based



Psyche-based



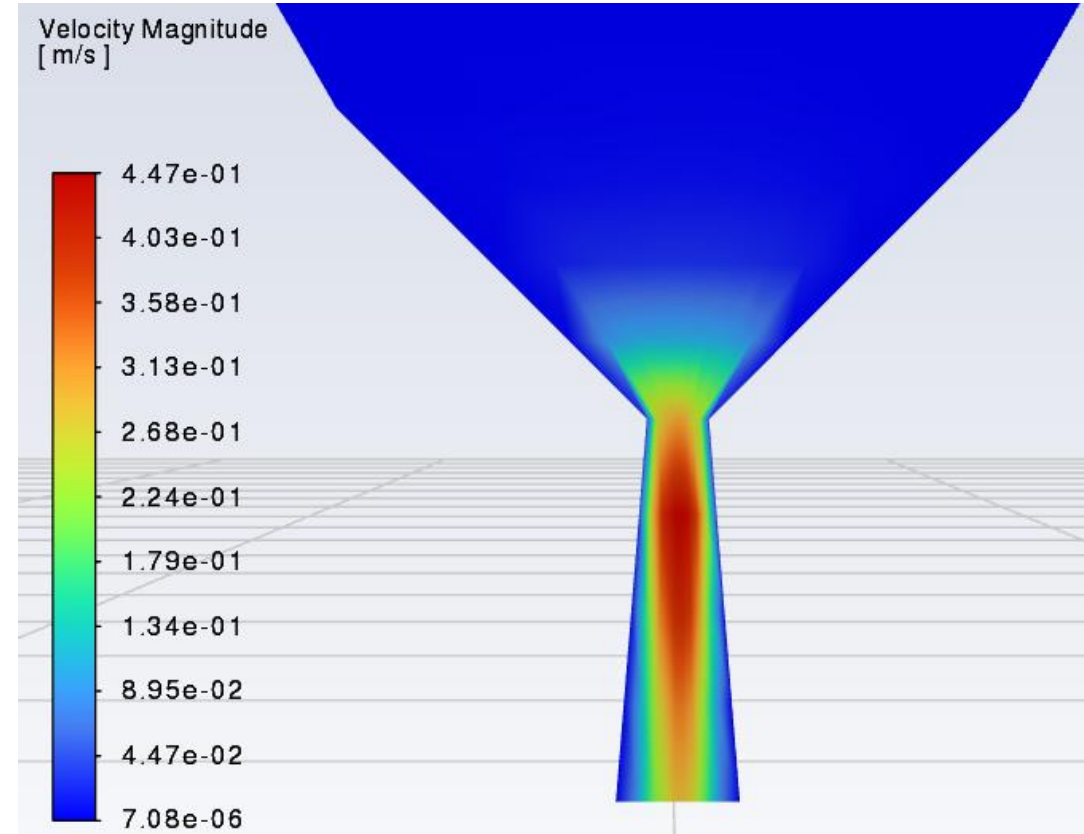
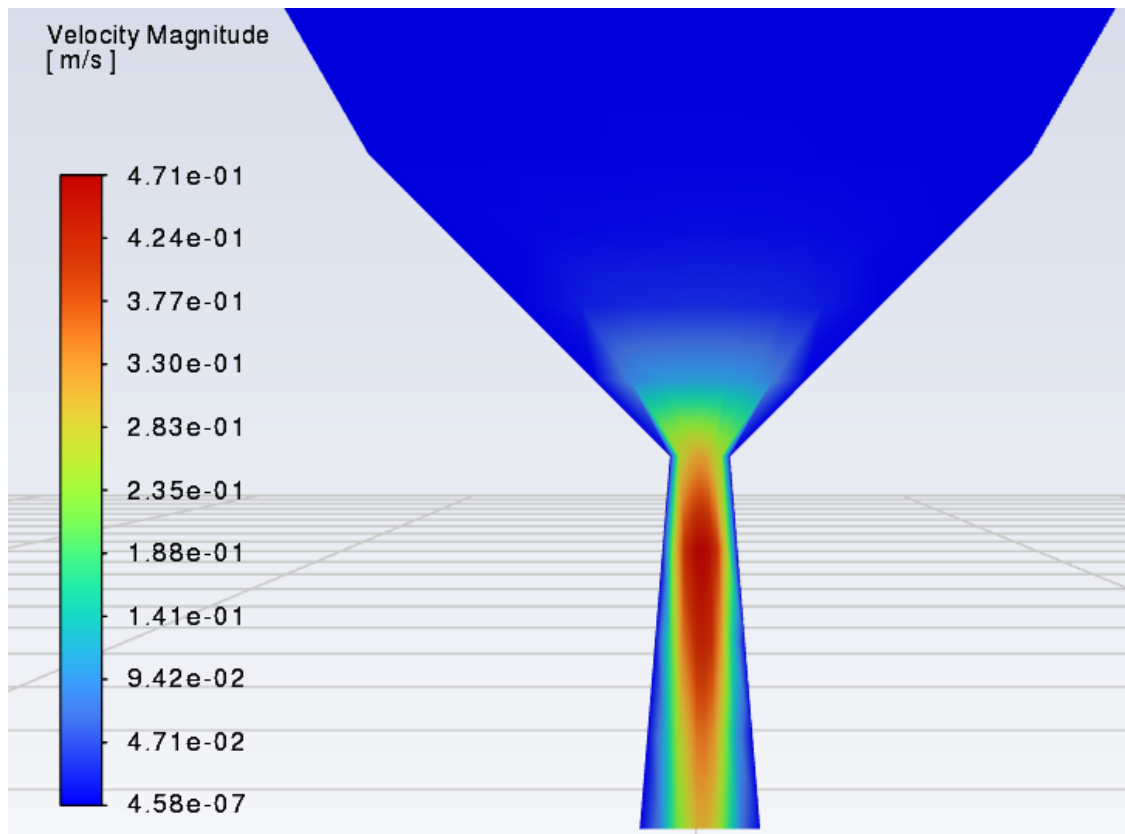
Results → Flow

Mass flow rate:
0.0008 kg/s

Velocity In:
0.001 m/s

Earth-based

Psyche-based



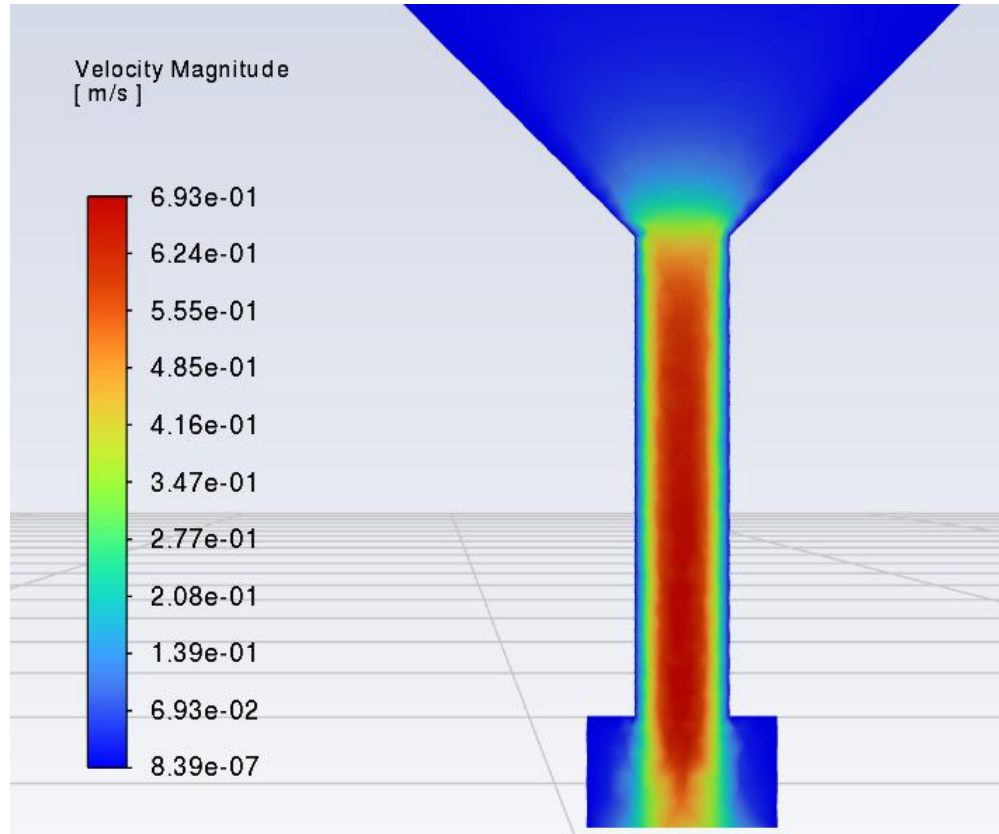
Results → Flow

Mass flow rate:
0.0008 kg/s

Velocity In:
0.001 m/s

Earth-based

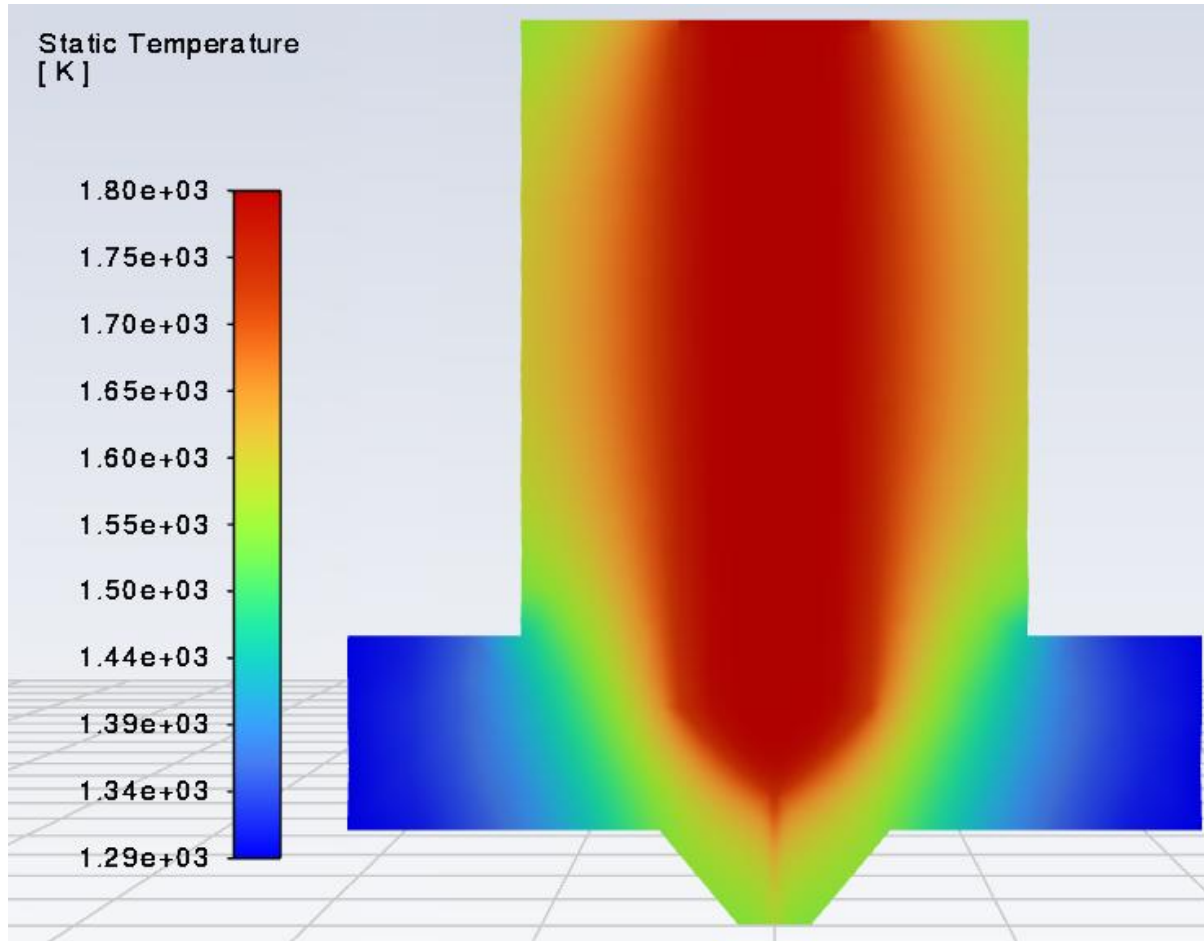
Psyche-based



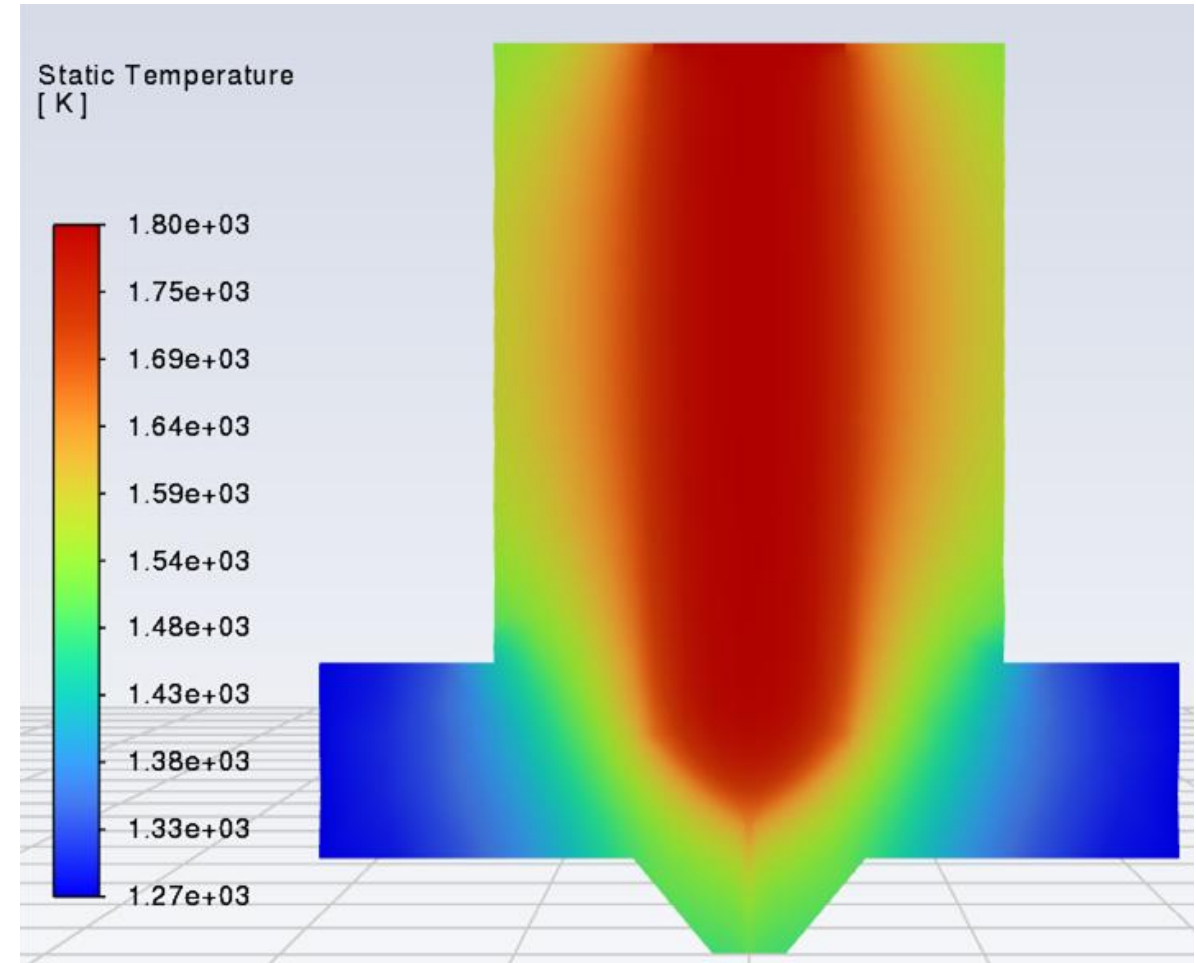
FAILED

Results → Thermal

Earth-based

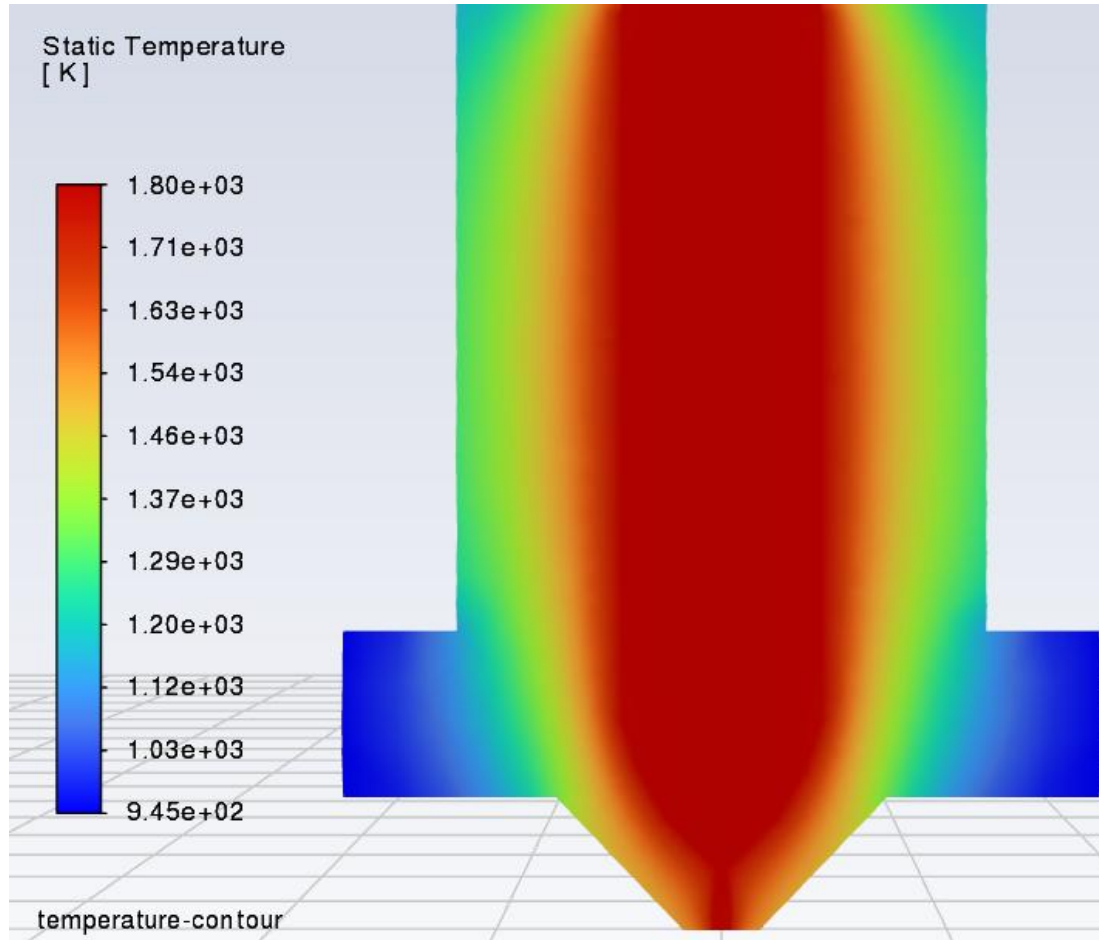


Psyche-based

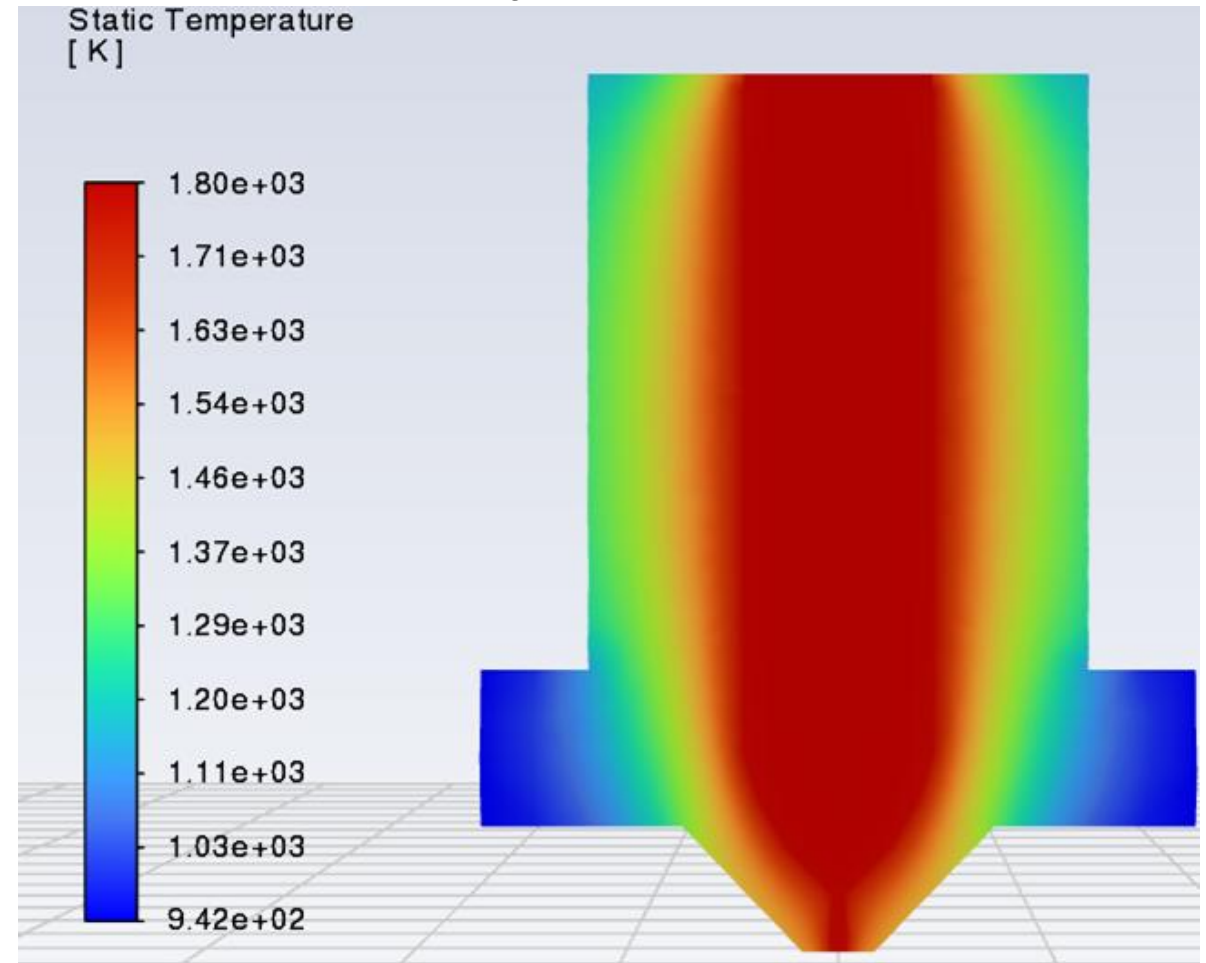


Results → Thermal

Earth-based

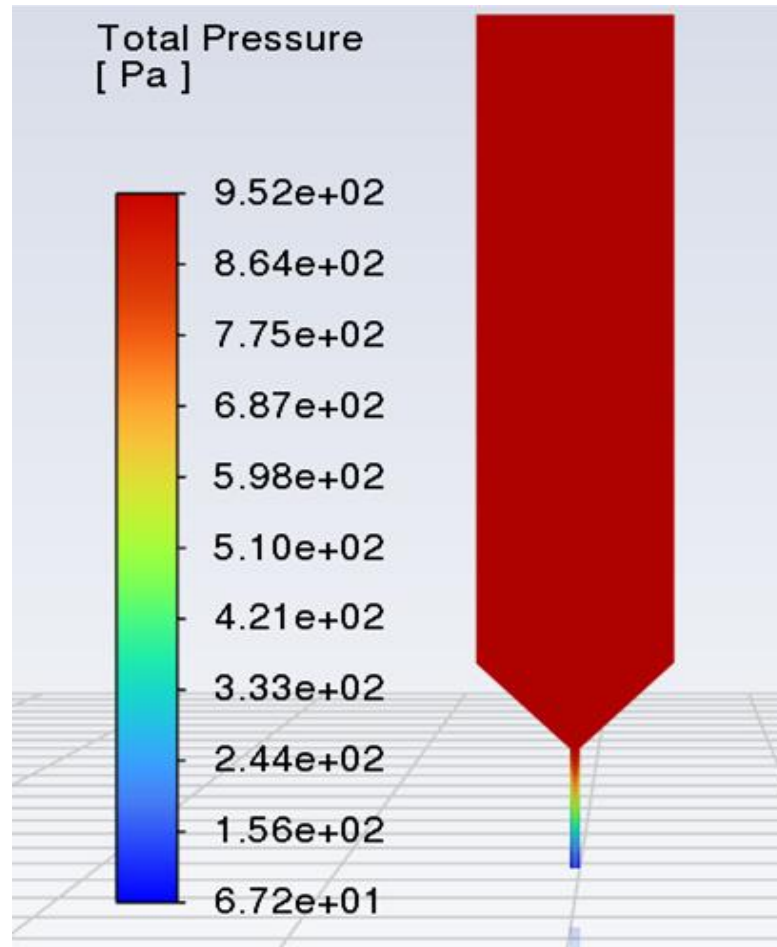


Psyche-based

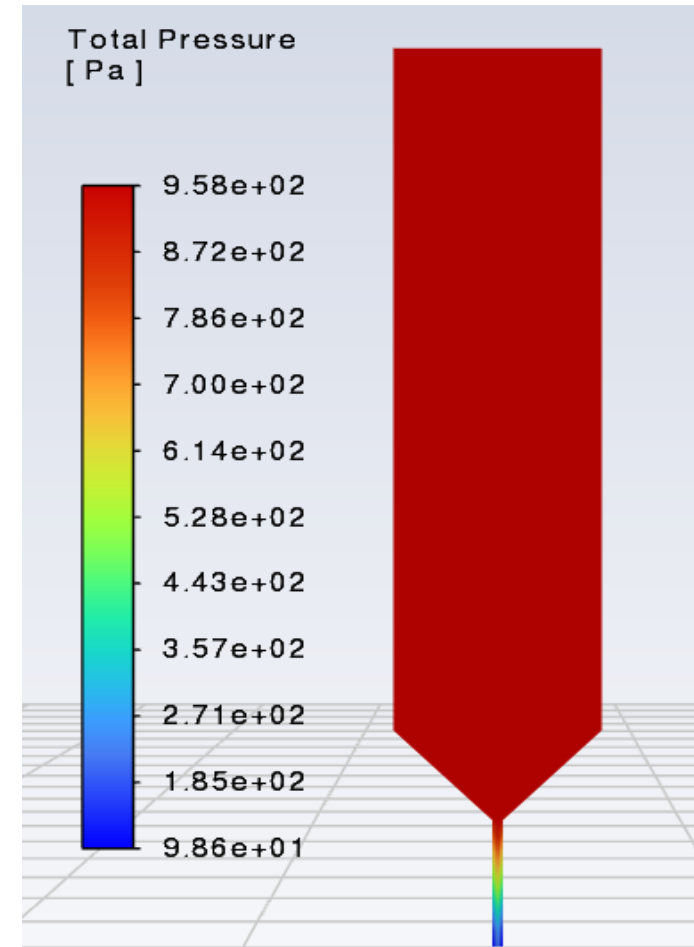


Results → Pressure

Earth-based

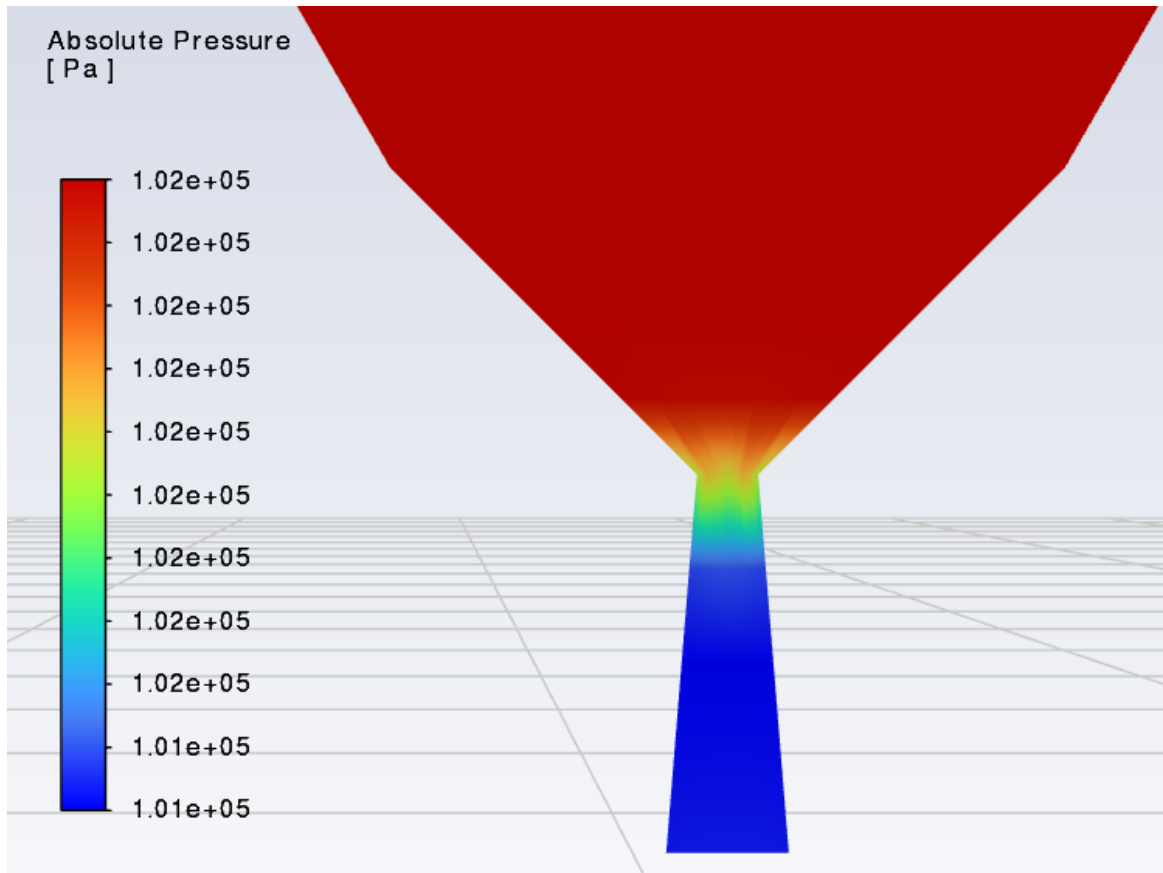


Psyche-based

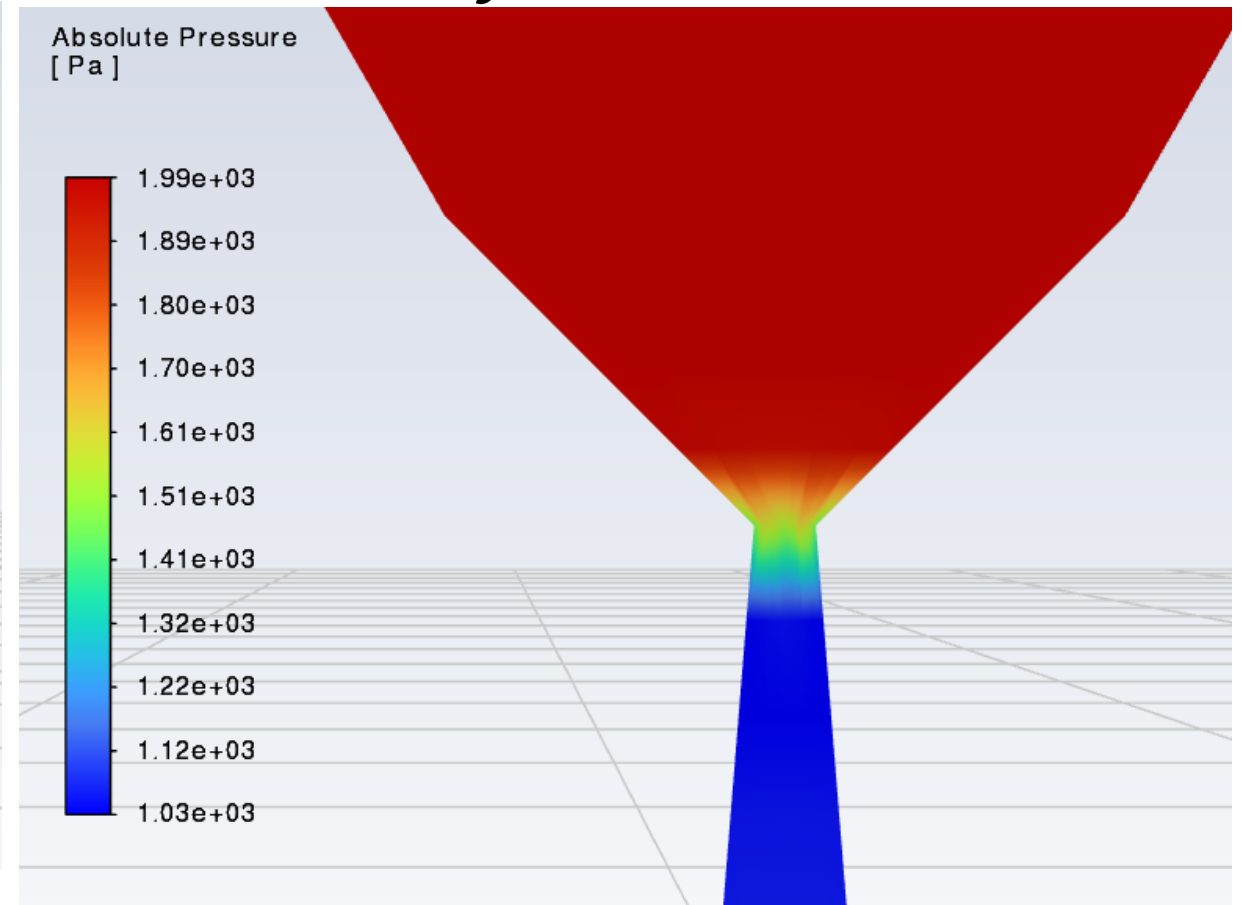


Results → Pressure

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

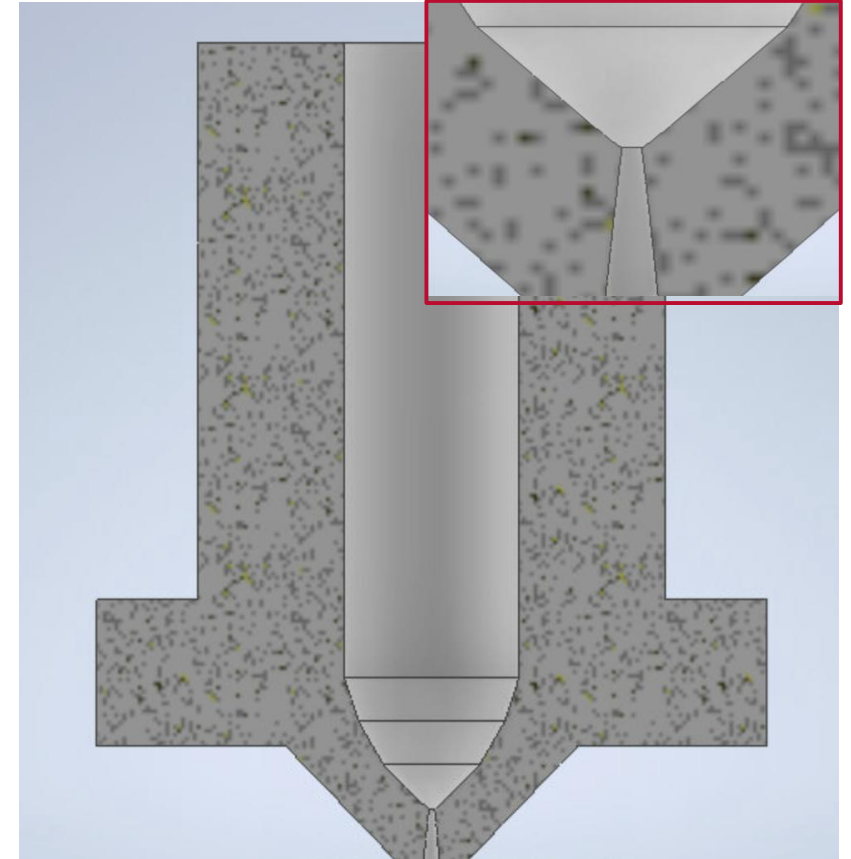
2. Fiber Orientation Control

- Has transverse flow component to align fibers
- Increases cross-path strength

3. Surface Ironing

- Smooths out top layer as it's deposited
- Helps with inter-layer adhesion

Converging-Diverging

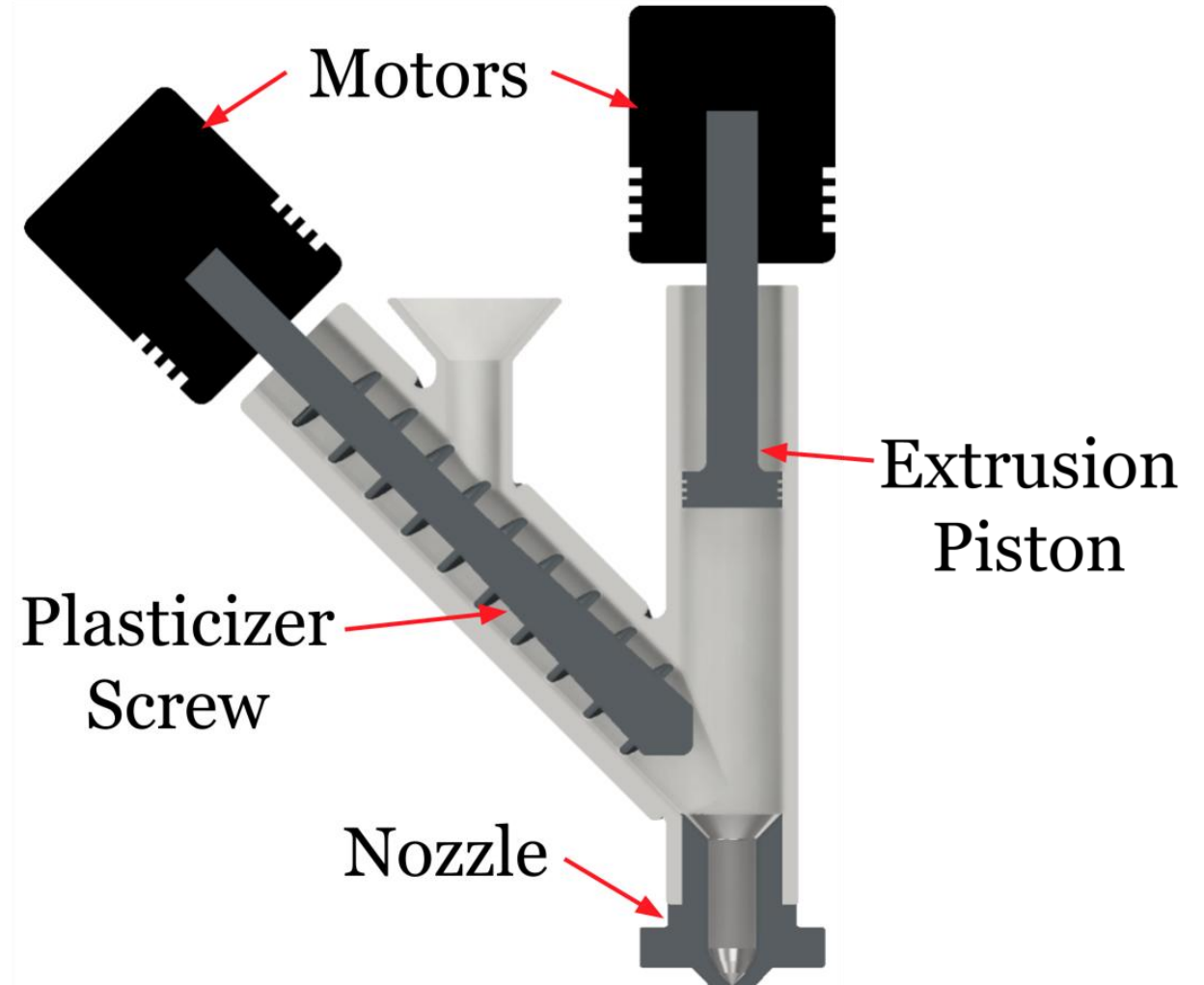
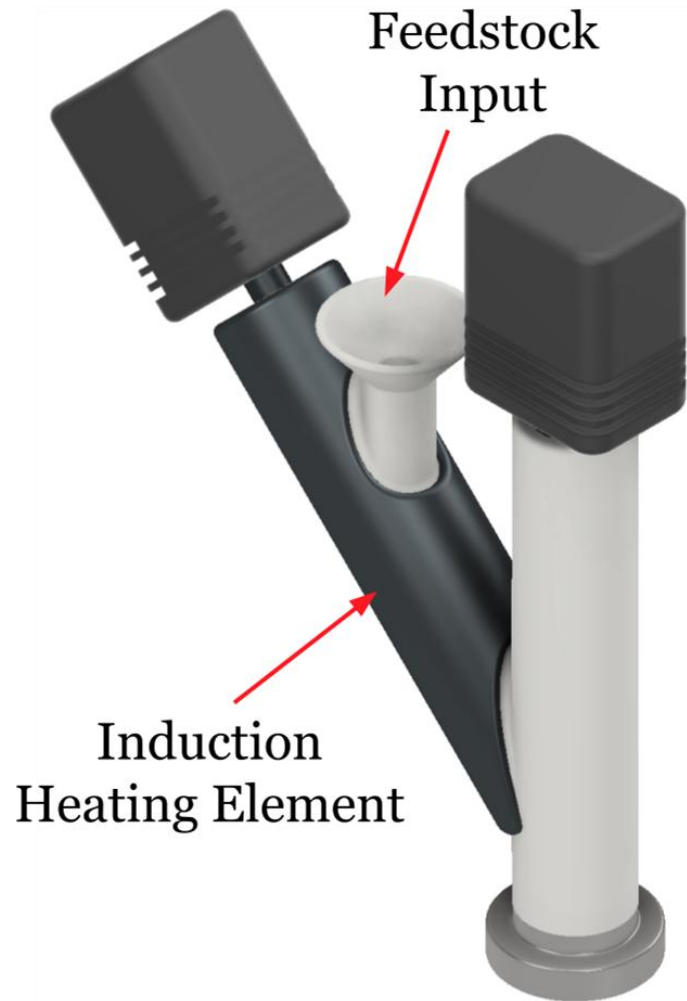


CAD Modeling

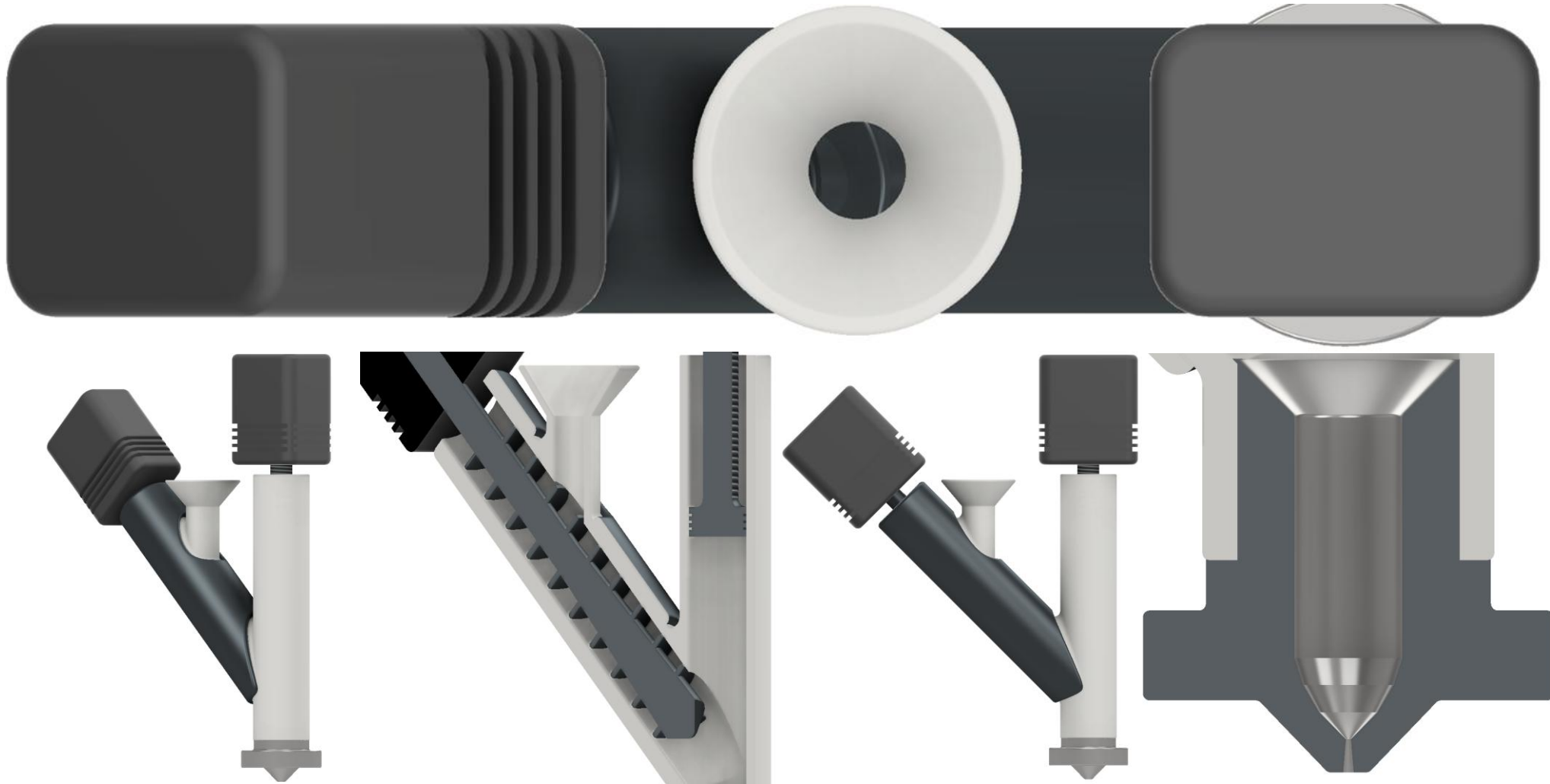
Proposed Extrusion Mechanism

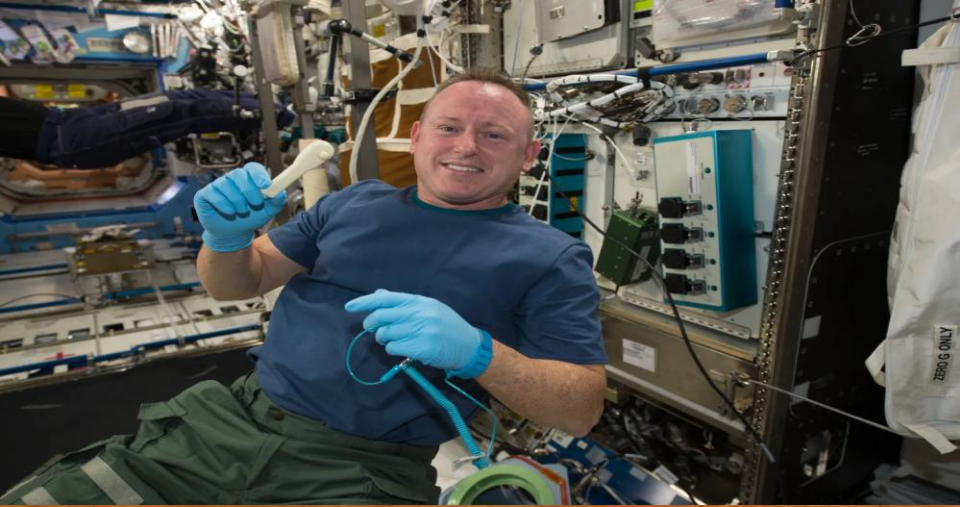


Proposed Extrusion Mechanism



Proposed Extrusion Mechanism





CONCLUSION

Summary and Future Works



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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

