Motor Sizing Analysis

Background:

A critical design decision during this project was sizing the drive motor for the auger screw inside of the extruder. As it turns out, this is no simple task. There are many factors influencing the torque required to drive the screw, including:

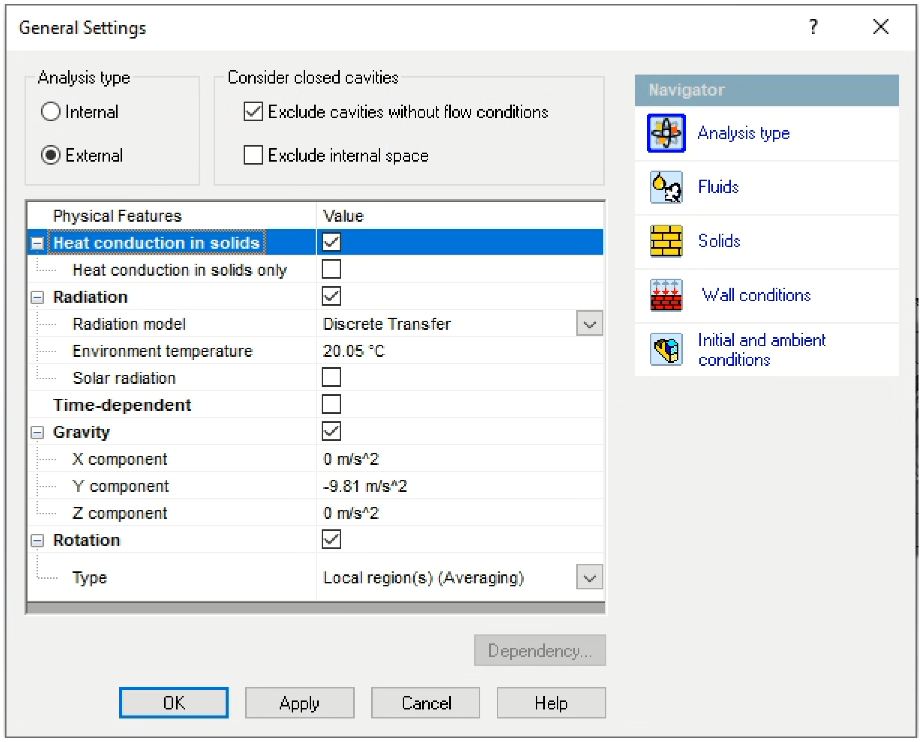
1. Frictional contact forces between the exterior of the screw and the inner diameter of the barrel
2. Shearing interactions between the auger screw and the multi-phase extrusion material
3. The pressure distribution developed due to the flight (taper) of the auger screw

Simple analytical models utilizing Bernoulli's equation without frictional losses (with known geometry and flow properties) yielded a "pump work" term of approximately 0.5W. This equated to a laughably incorrect drive torque of 0.046 N*m required. From this computation, it was evident that the frictional forces involved in this process are not only not negligible, they likely constitute the majority of the drive torque required.

After further investigation into potential analytical solution methods to this problem, it became evident that computational methods would have to be implemented, as such methods don't exist.

Computational Fluid Dynamics Solution Method:

In order to computationally determine the motor torque required to drive the auger screw, a CFD Simulation was created in Solidworks. This was a very complex simulation—after many hours, numerous attempts, and poring over Solidworks's Technical Reference for Flow Simulations Manual, a combination of inputs and solver settings that allowed for accurate results were finally determined. The simulation consisted of the parameters shown by Figures 1-7.

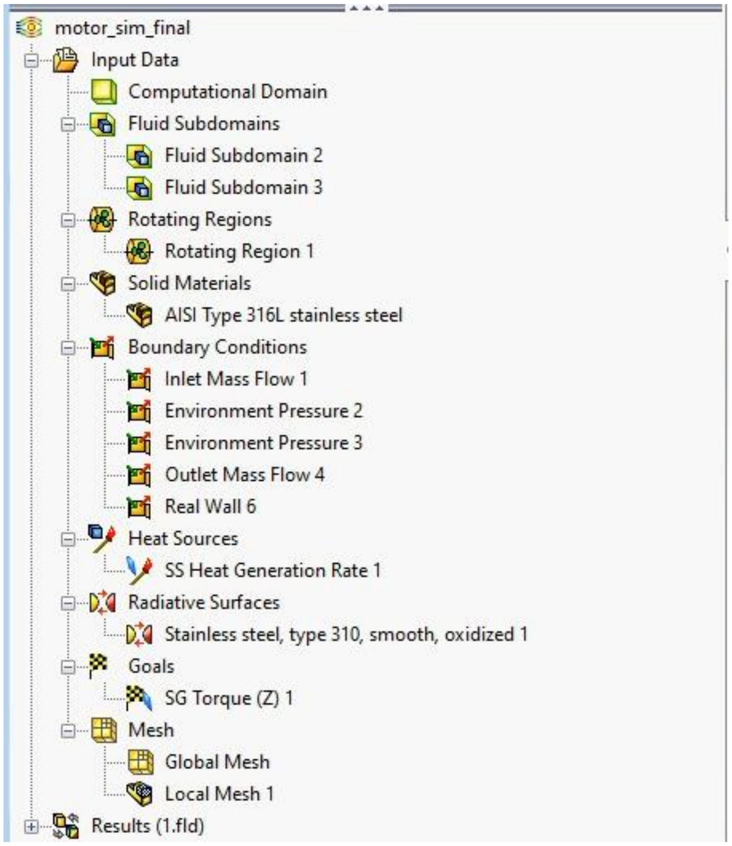


Analysis type
○ Internal
● External

Consider closed cavities
☑ Exclude cavities without flow conditions
☐ Exclude internal space

Physical Features	Value
Heat conduction in solids	☑
Heat conduction in solids only	☐
Radiation	☑
Radiation model	Discrete Transfer
Environment temperature	20.05 °C
Solar radiation	☐
Time-dependent	☐
Gravity	☑
X component	0 m/s^2
Y component	-9.81 m/s^2
Z component	0 m/s^2
Rotation	☑
Type	Local region(s) (Averaging)

Figure 1: Simulation Settings



- motor_sim_final
  - Input Data
    - Computational Domain
    - Fluid Subdomains
      - Fluid Subdomain 2
      - Fluid Subdomain 3
    - Rotating Regions
      - Rotating Region 1
    - Solid Materials
      - AISI Type 316L stainless steel
    - Boundary Conditions
      - Inlet Mass Flow 1
      - Environment Pressure 2
      - Environment Pressure 3
      - Outlet Mass Flow 4
      - Real Wall 6
    - Heat Sources
      - SS Heat Generation Rate 1
    - Radiative Surfaces
      - Stainless steel, type 310, smooth, oxidized 1
    - Goals
      - SG Torque (Z) 1
    - Mesh
      - Global Mesh
      - Local Mesh 1
  - Results (1.fld)

Figure 2: Simulation Inputs

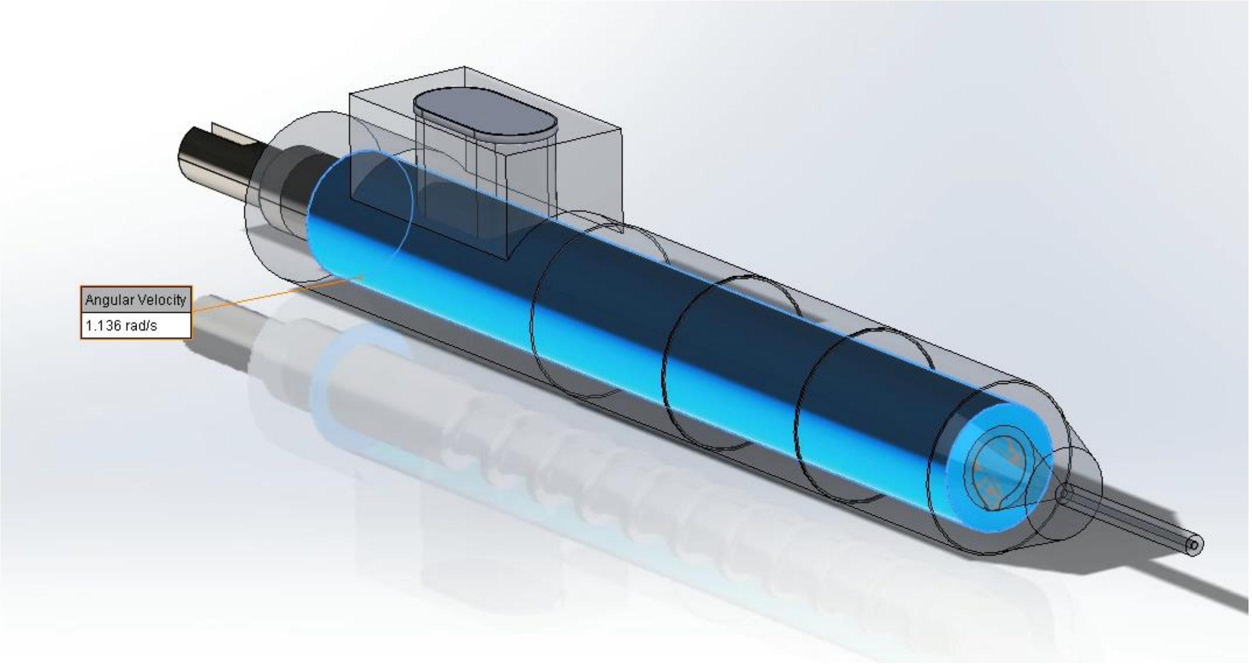


Figure 3: Rotating Region

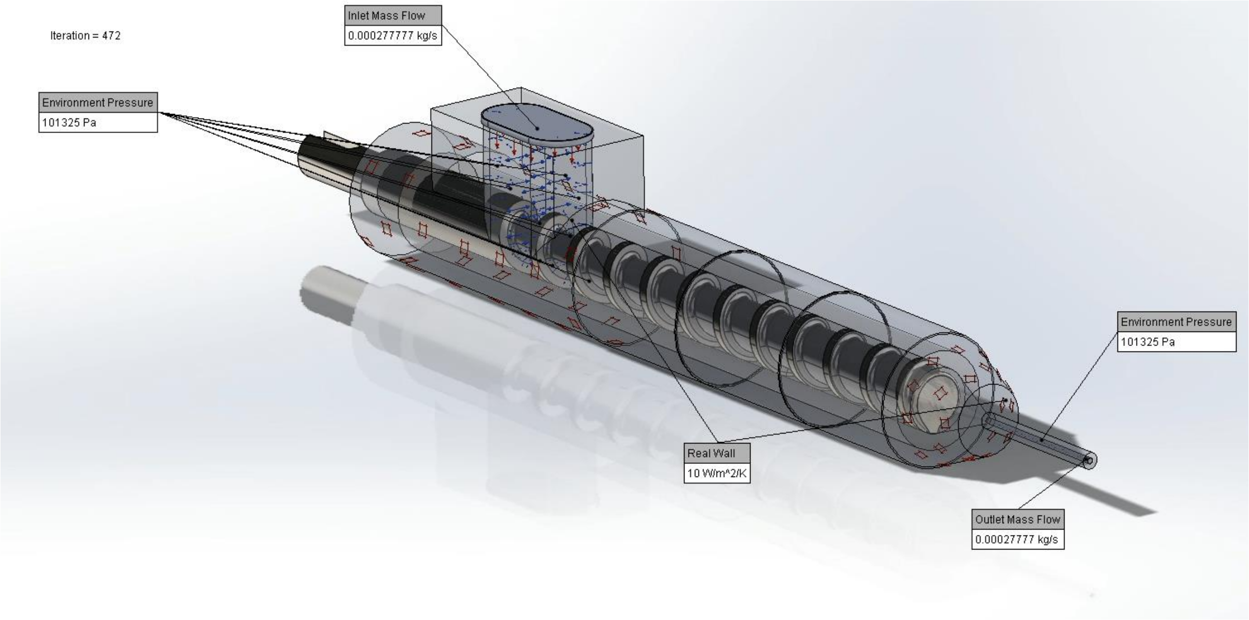


Figure 4: Boundary Conditions

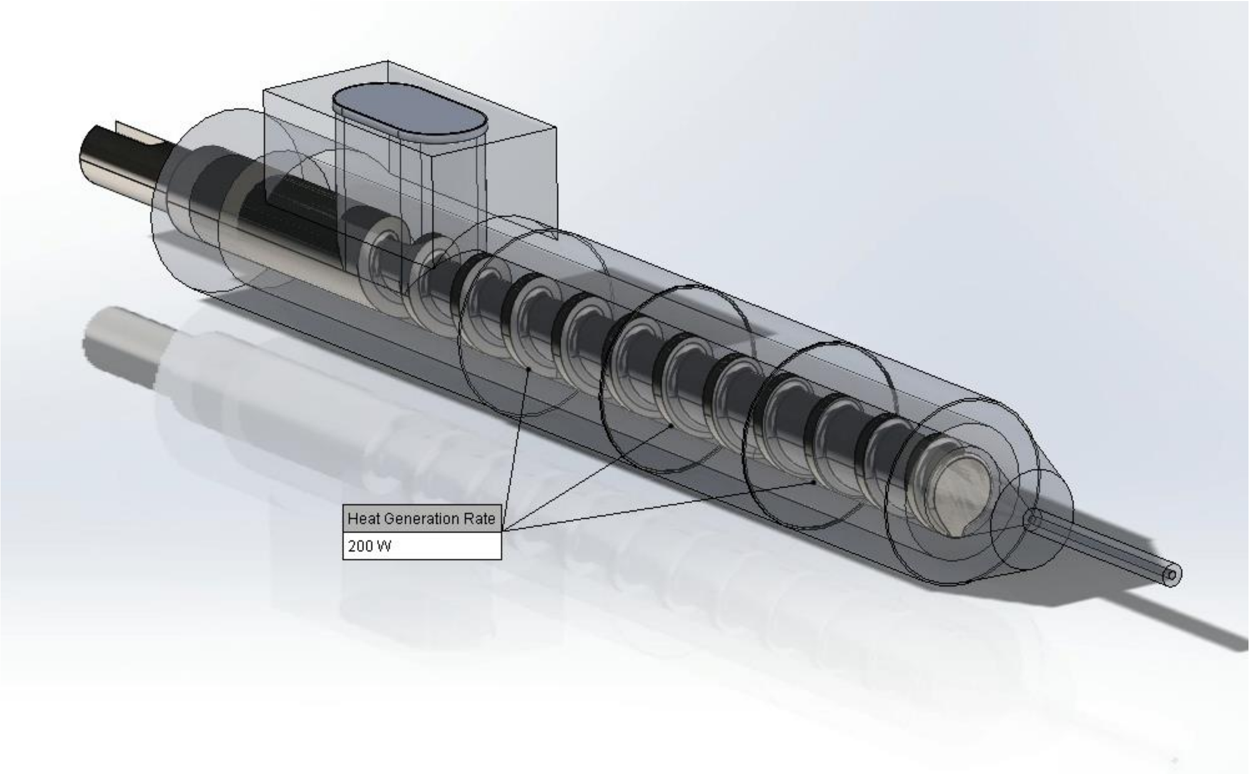
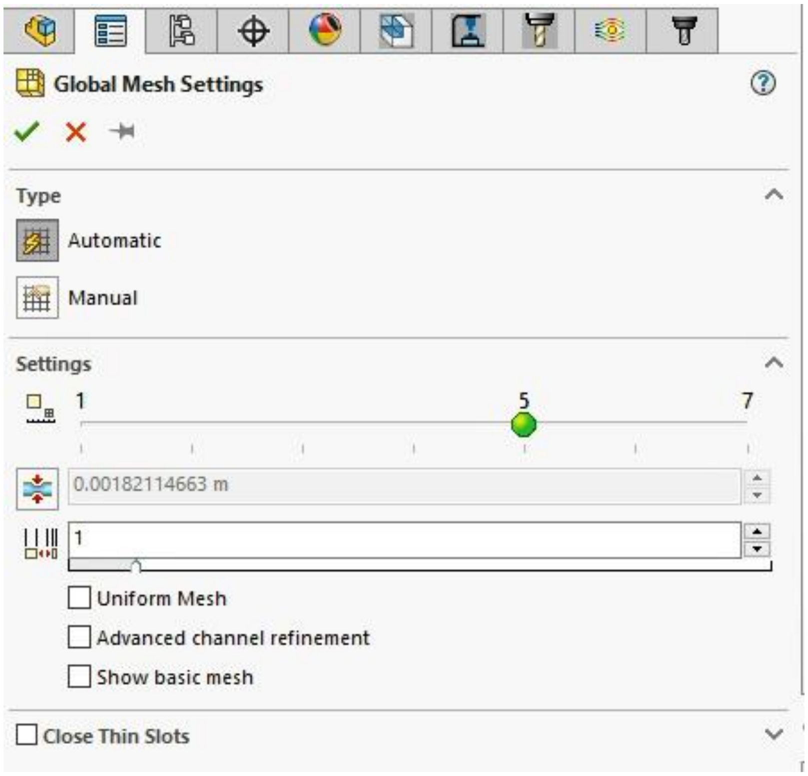


Figure 5: Heater Settings



Global Mesh Settings

Type

● Automatic

○ Manual

Settings

1 5 7

0.00182114663 m

1

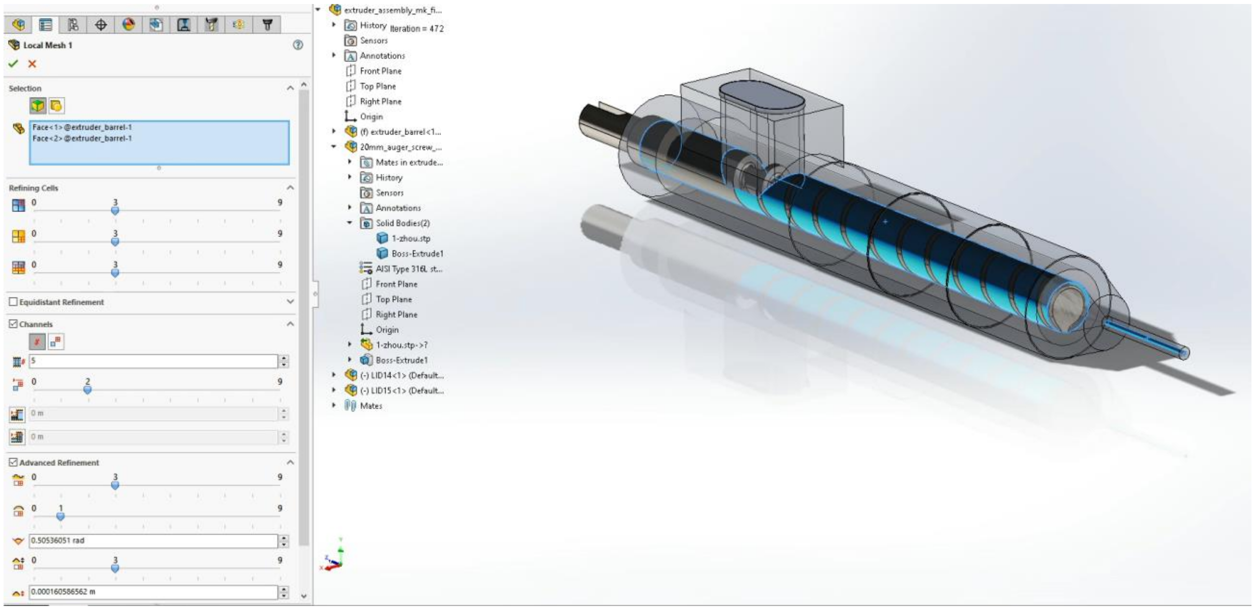
☐ Uniform Mesh

☐ Advanced channel refinement

☐ Show basic mesh

☐ Close Thin Slots

Figure 6: Global Mesh Settings


Local Mesh 1

Selection

Face<1>@extruder_barrel-1
Face<2>@extruder_barrel-1

Refining Cells

0 3 9
0 3 9
0 3 9

☐ Equidistant Refinement

☑ Channels

5
0 2 9
0 m
0 m

☑ Advanced Refinement

0 3 9
0 1 9
0.50536051 rad
0 3 9
0.000160586562 m

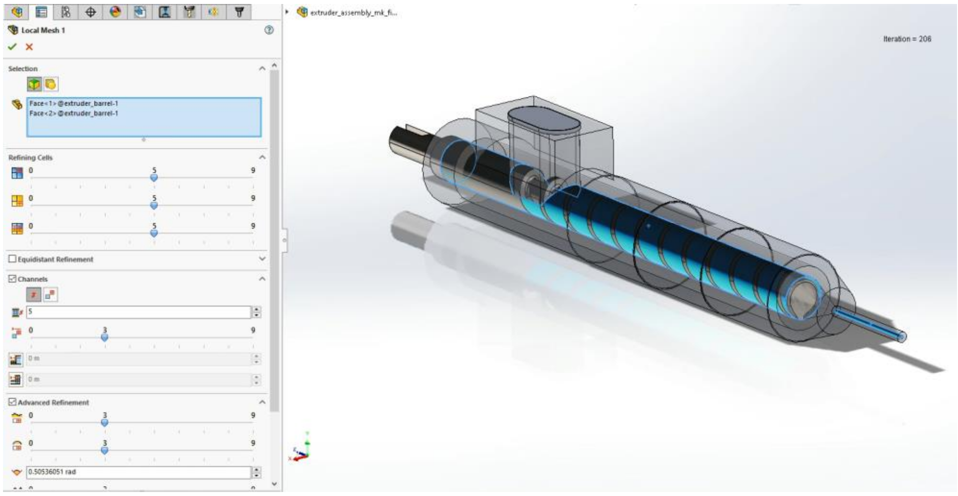
Figure 7: Local Mesh Settings

To summarize the simulation settings indicated by Figures 1-7:

- An external flow analysis was selected
- The simulation considered conduction, convection, radiation, gravity, and rotation
- A steady-state solver was selected
- The extruder was immersed in atmospheric air
- The interior fluid consisted of LDPE (Low Density Polyethylene)
- A heat transfer coefficient was prescribed at the outer surface of the extruder
- A relatively fine global mesh was used
- An additional local mesh was defined at the interior of the barrel, including the walls of the barrel

Verification of Simulation (Mesh Independence):

In CFD one of the most critical things to investigate is the mesh dependency of your results. If the simulation is accurate, the results between a coarse mesh and a fine mesh should be a consistent with one another. They may slightly differ in value due to the difference in resolution of the models, but they should not vary drastically. This property was verified by creating a simulation with over 800 thousand cells compared to the 200k considered prior. The mesh settings for the higher resolution simulation are shown by Figure 8.



Selection

Face<1>@extruder_barrel-1
Face<2>@extruder_barrel-1

Refining Cells: 5 / 5 / 5 (0–9)

☐ Equidistant Refinement

☑ Channels: 5; 3 (0–9); 0 m; 0 m

☑ Advanced Refinement: 3 (0–9); 3 (0–9); 0.50536051 rad

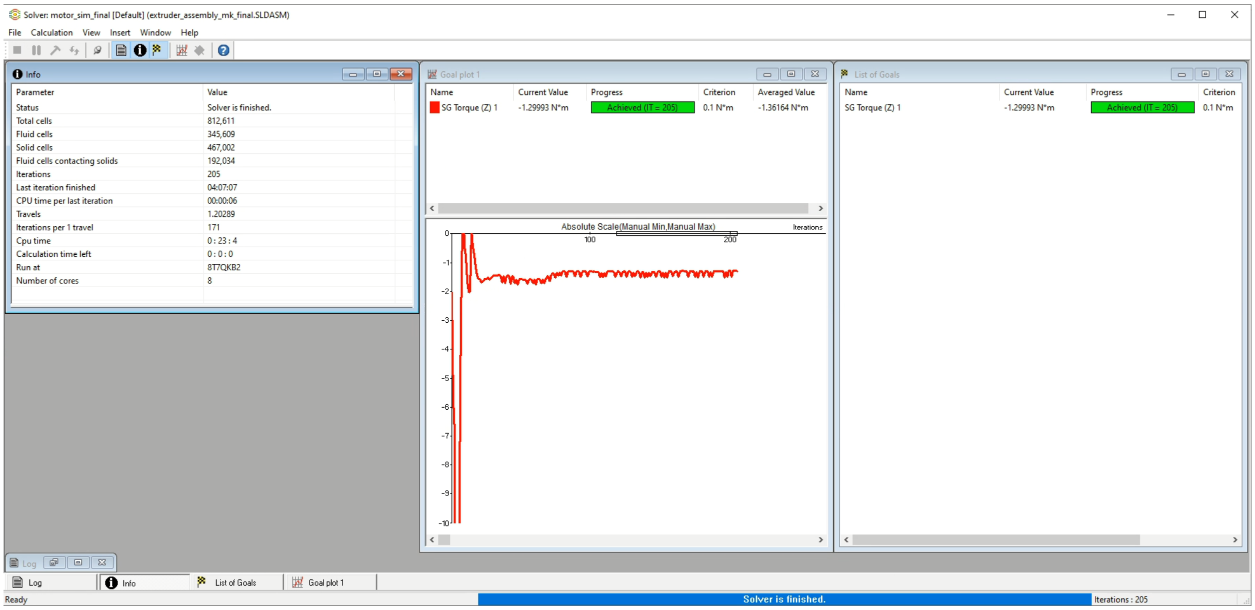
Figure 8: Local Mesh High Resolution Simulation Settings

The results for the magnitude of the motor torque required to drive the auger screw between the two otherwise identical models consisted of the following:

Lower Resolution Simulation (see Figure 13): 1.29867 N*m

High Resolution Simulation (see Figure 9 below): 1.29999 N*m

Percent Error: 0.10%



Solver: motor_sim_final [Default] (extruder_assembly_mk_final.SLDASM)

Parameter	Value
Status	Solver is finished.
Total cells	812,611
Fluid cells	345,609
Solid cells	467,002
Fluid cells contacting solids	192,034
Iterations	205
Last iteration finished	04:07:07
CPU time per last iteration	00:00:06
Travels	1.20289
Iterations per 1 travel	171
Cpu time	0 : 23 : 4
Calculation time left	0 : 0 : 0
Run at	8T7QKB2
Number of cores	8

Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-1.29993 N*m	Achieved (IT = 205)	0.1 N*m	-1.36164 N*m

Name	Current Value	Progress	Criterion
SG Torque (Z) 1	-1.29993 N*m	Achieved (IT = 205)	0.1 N*m

Solver is finished.

Iterations : 205

Figure 9: High Resolution Simulation Convergence Data

The simulation was also validated by analyzing velocity, temperature, and pressure distributions.

Execution of Simulation to Determine Motor Torque Required to Drive Auger Screw:

With the validity of the simulation established, testing to determine the influence of fluid temperature on motor torque required could begin. First, four different temperatures were considered: 100 °C, 150 °C, 200 °C, and 250 °C. Note that these temperatures were the initial conditions of both the fluid and the solid comprising the model. With all other simulation inputs left unchanged, the results were as shown by Figure 10.

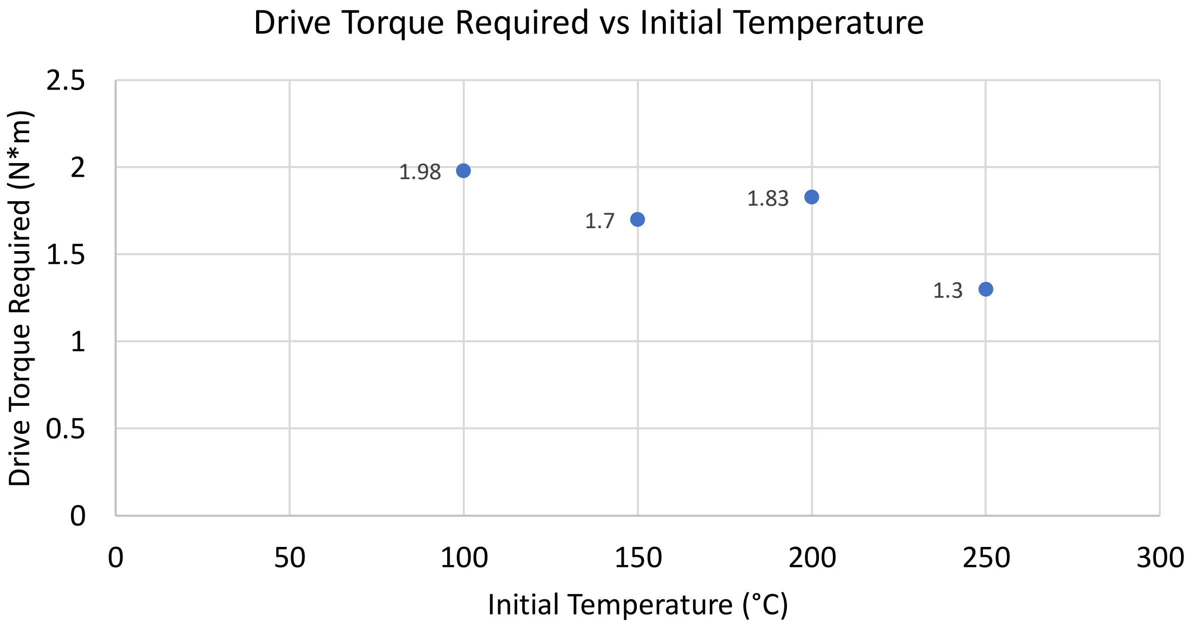
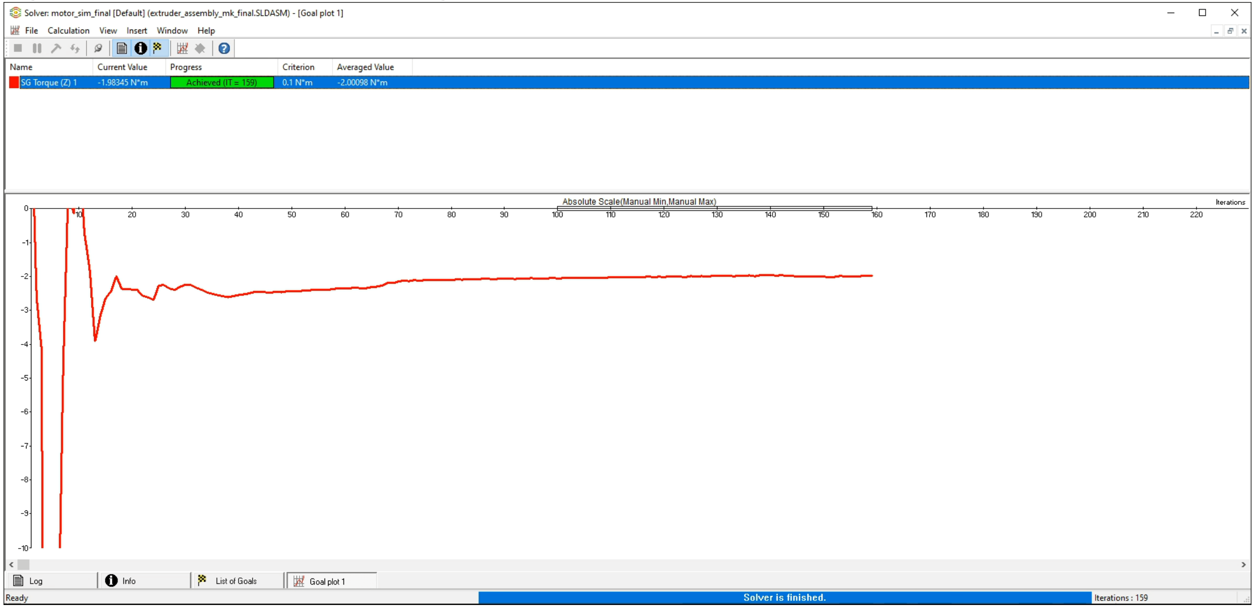


Figure 10: Drive Torque Required vs Initial Temperature Steady State

Figures 11-14 indicate the convergence data for each simulation.



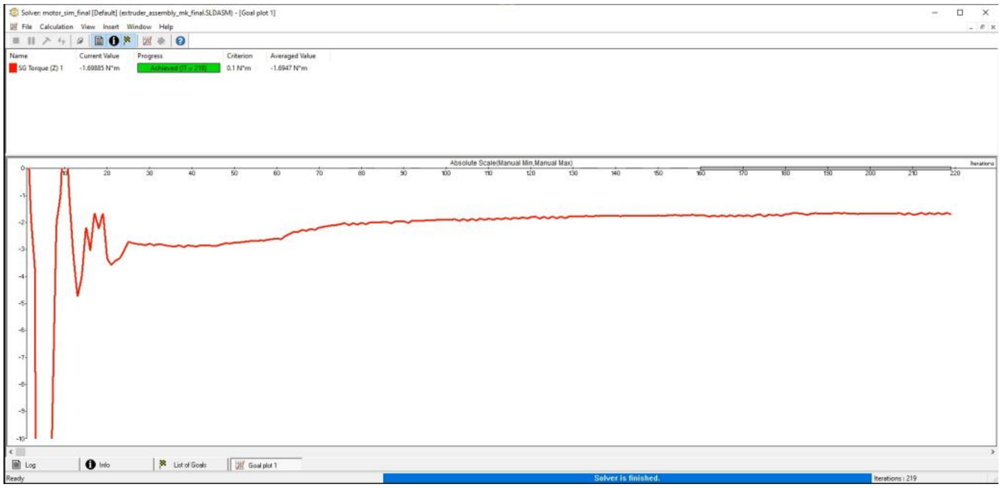
Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-1.98345 N*m	Achieved (IT = 159)	0.1 N*m	-2.00098 N*m

Ready

Solver is finished.

Iterations : 159

Figure 11: 100 C Initial Condition Convergence

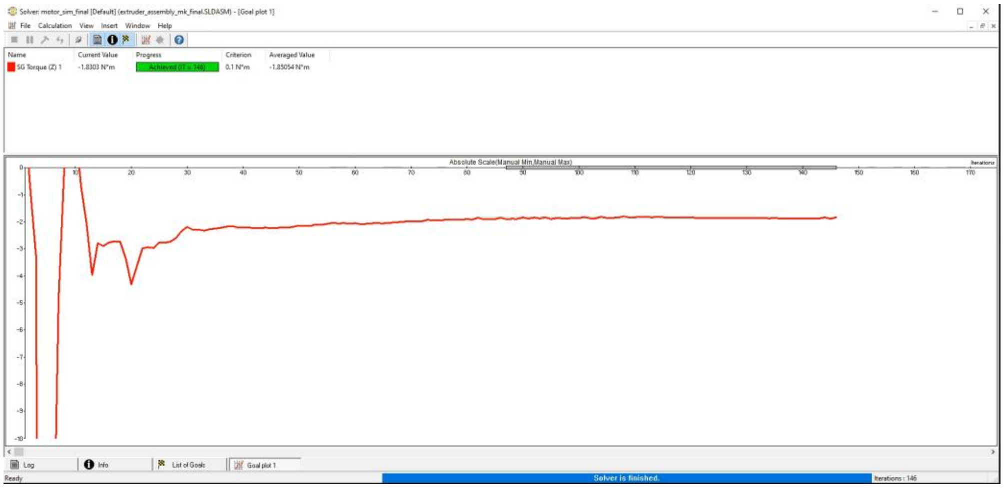


Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-1.69885 N*m	Achieved (IT = 219)	0.1 N*m	-1.6947 N*m

Solver is finished.

Iterations : 219

Figure 12: 150 C Initial Condition Convergence

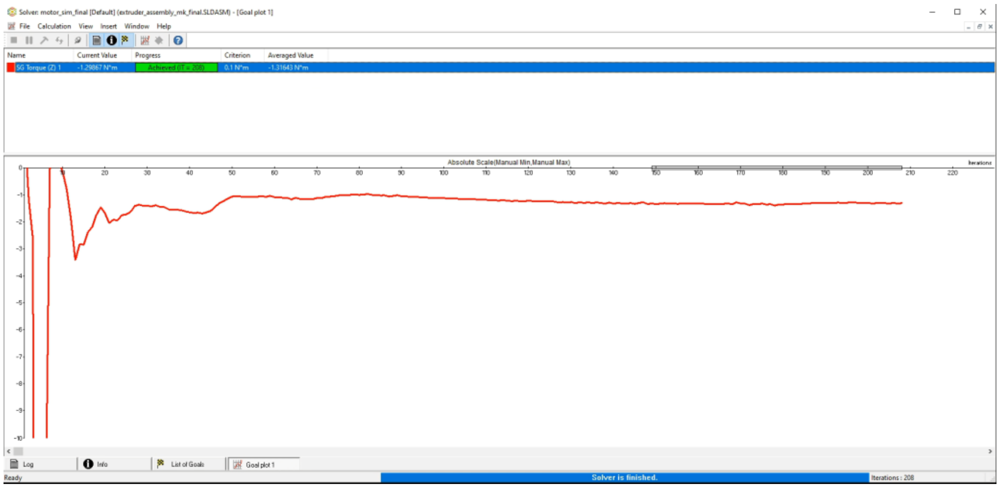


Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-1.8303 N*m	Achieved (IT = 146)	0.1 N*m	-1.85054 N*m

Solver is finished.

Iterations : 146

Figure 13: 200 C Initial Condition Convergence



Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-1.29867 N*m	Achieved (IT = 208)	0.1 N*m	-1.31643 N*m

Solver is finished.

Iterations : 208

Figure 14: 250 C Initial Condition Convergence

Figures 15-17 show some visual results of the 250 ° initial condition simulation.

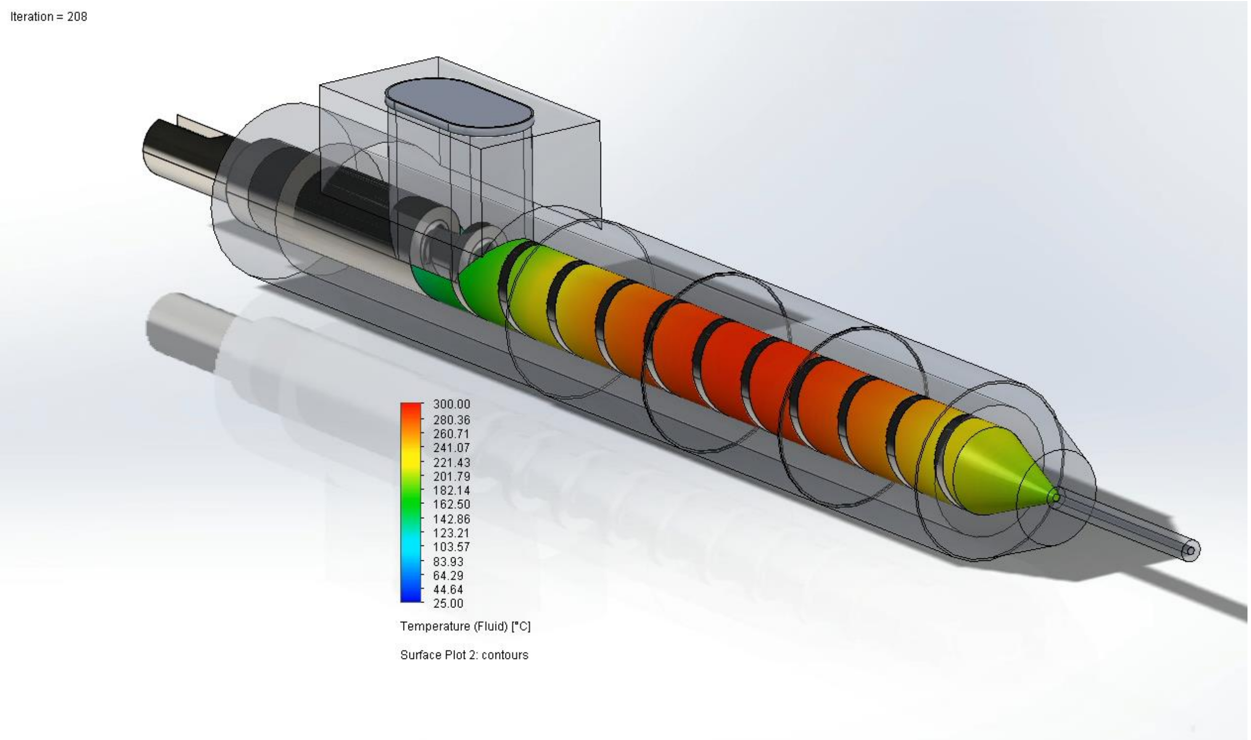


Figure 15: Final Fluid Temperature Distribution for 250 C Initial Condition

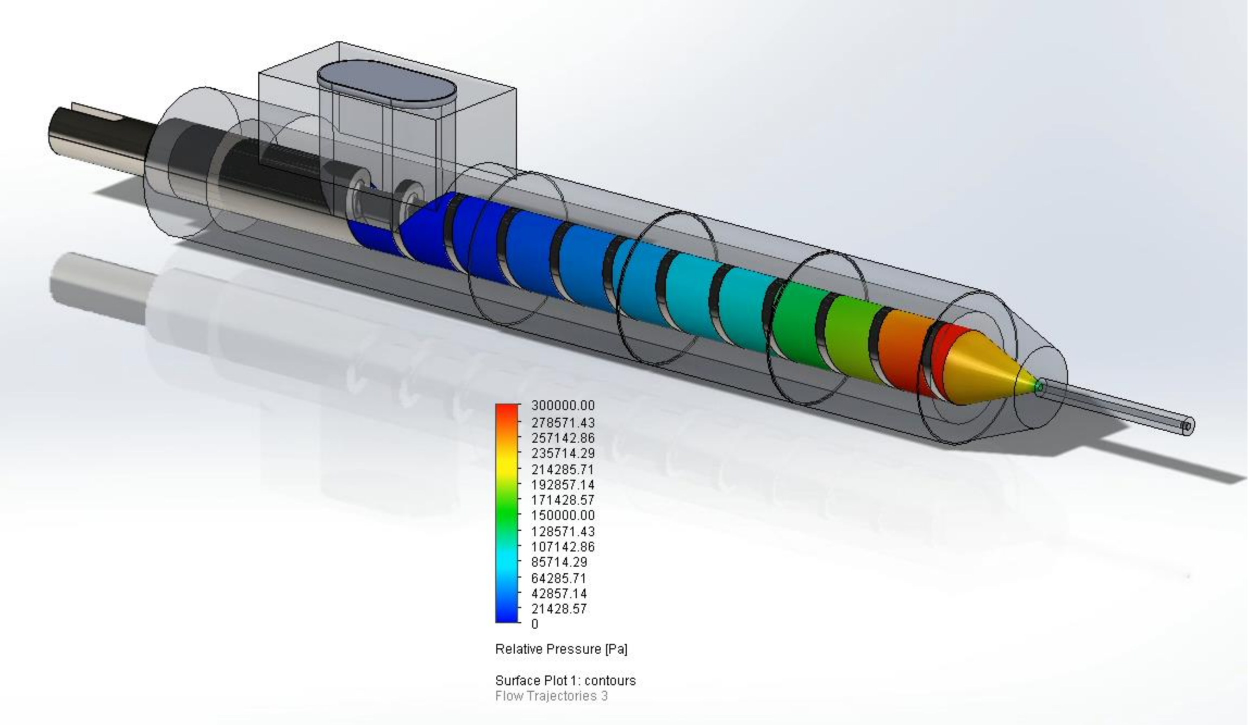


Figure 16: Pressure Distribution Inside of Barrel

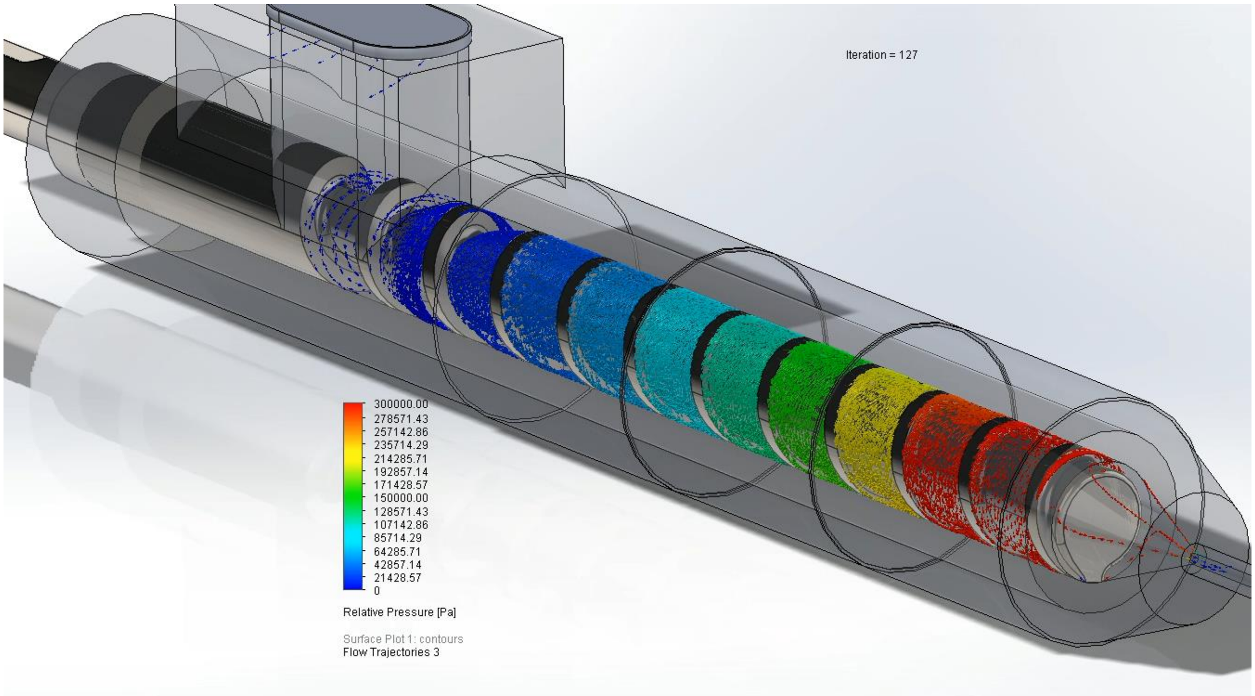
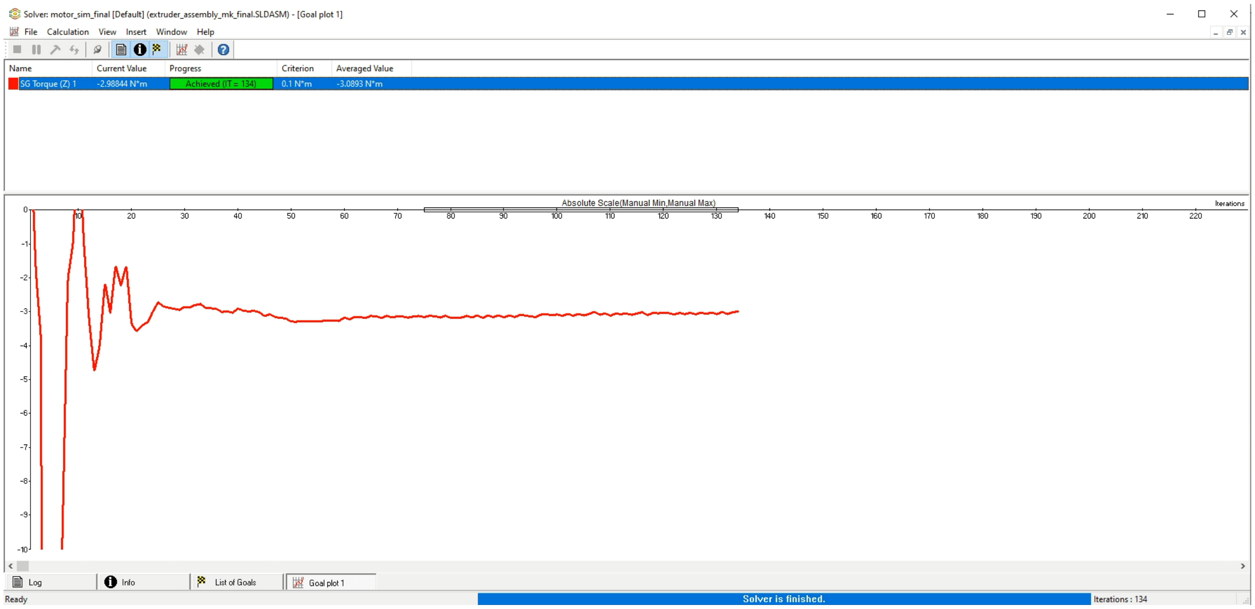


Figure 17: Pressure Distribution Inside of Barrel with Arrows

Note that the manufacturer’s specified compression ratio for the auger screw used in this simulation is 2.8 to 1. Meaning that a pressure of approximately 280kPa should be expected near the end of the barrel. The simulation results match very well with this, further confirming the validity of the model. In addition, the resulting pressure distribution was unaltered across all initial temperature tests done (and other analyses not included in this write-up).

Next, the maximum torque required to drive the auger screw was desired. In order to find this value, some worst case and transient analyses were considered. First, a 100 °C steady state analysis was conducted. The heating elements and wall conditions were modified in an attempt to maintain a constant temperature of 100 °C (at this temperature the fluid would be quite difficult to extrude). The convergence data for this simulation is shown by Figure 18.



Name	Current Value	Progress	Criterion	Averaged Value
SG Torque (Z) 1	-2.98844 N*m	Achieved (IT = 134)	0.1 N*m	-3.0893 N*m

Figure 18: Constant 100 C Convergence Data

By reviewing Figure 18, it is evident that a new maximum required torque of the drive motor had been determined to be approximately 3 N*m.

To further investigate the maximum motor torque required, a transient analysis was conducted in order to find the "startup torque" of the motor. It would be anticipated that the maximum load on the motor would be at the beginning of use, as it has to overcome all static friction forces and set the fluid into motion. Figures 19 depicts this result.

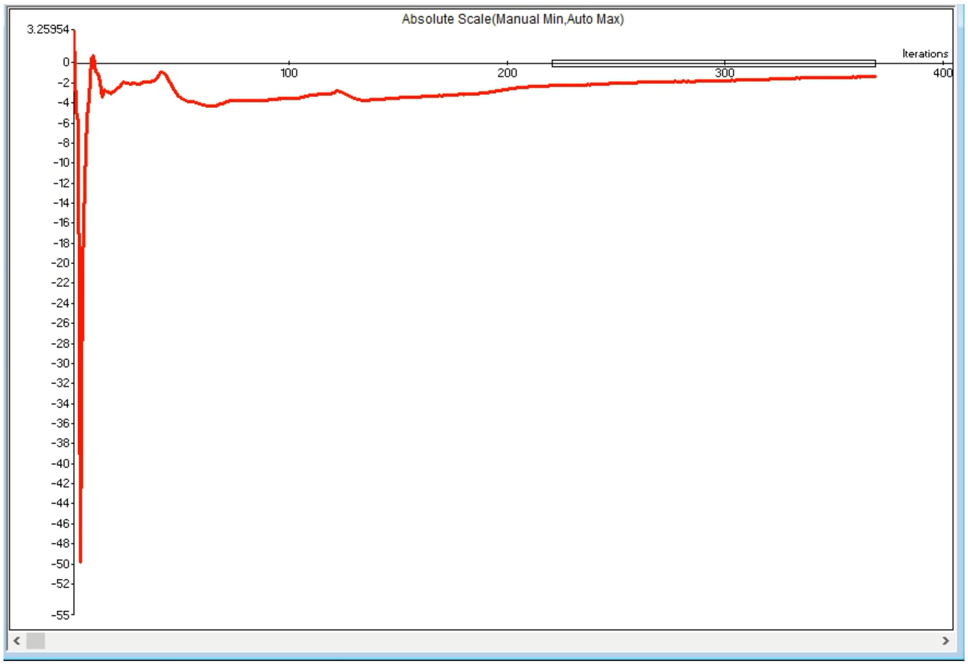


Figure 19: Startup Torque Testing

By reviewing Figure 19 and all other convergence data Figures, some important trends can be realized. There is a large spike in the drive torque required at the beginning of the simulation. This could be due to the inaccuracy of the solution for a very small number of iterations, or it could be indicating that a large drive torque is initially required. In order to investigate this matter further, a more complex transient analysis (including a sliding mesh instead of averaging local region for the rotating region) was conducted with over 8 million cells. Figure 20 depicts these results.

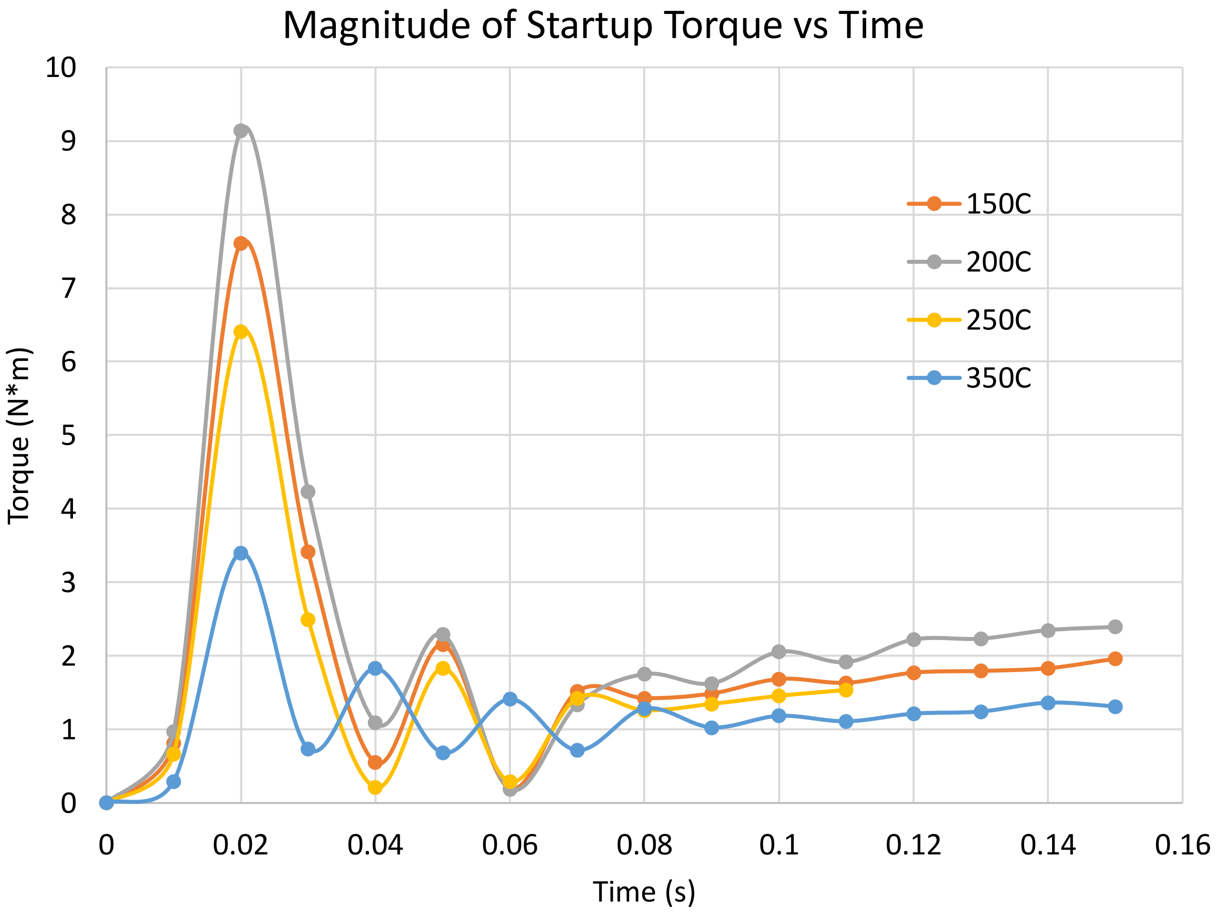
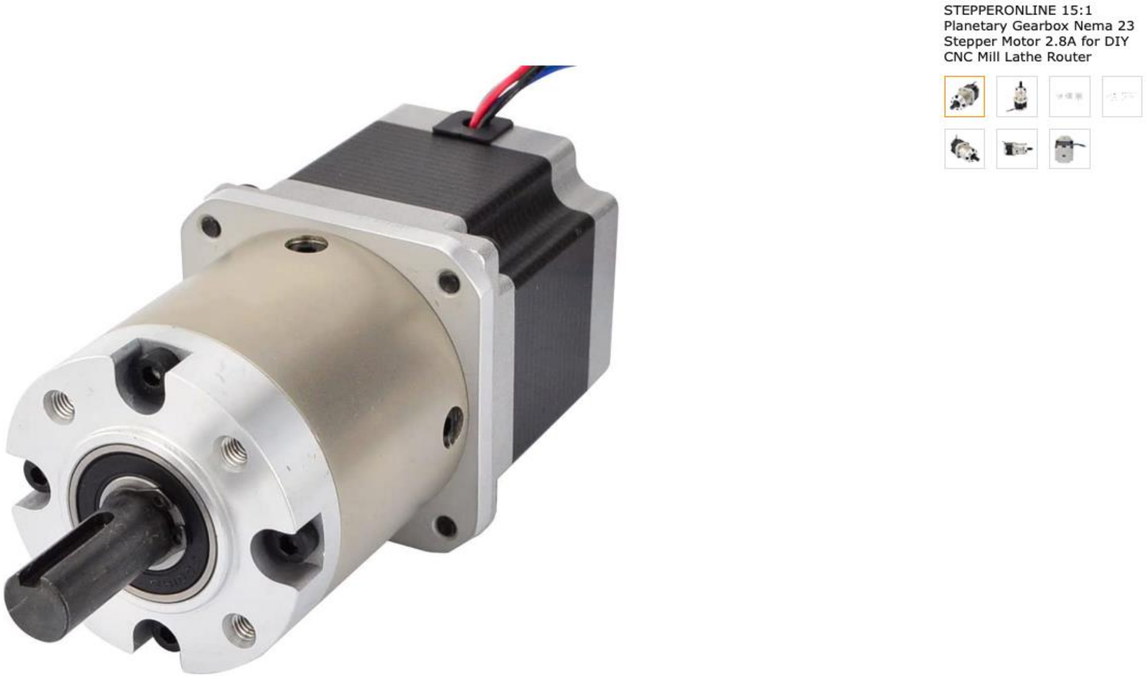


Figure 20: Startup Torque Transient Testing with Sliding Mesh

By reviewing Figure 20, it is evident that the trends shown for the temperatures considered match with that of Figure 10 very well. In addition, a new maximum torque of approximately 9.1 N*m had been determined. It is important to note that in these simulations, the auger screw itself is not in motion, the fluid is set into motion around the auger screw. This means that frictional forces between the auger screw and the barrel itself are neglected. The fit between the exterior of the auger screw and the interior of the barrel is meant to be of “transitional” type, leaning more towards the “loose” end of the spectrum, so this may also play a role in the magnitude of the drive torque required. However, it is expected to be relatively small.

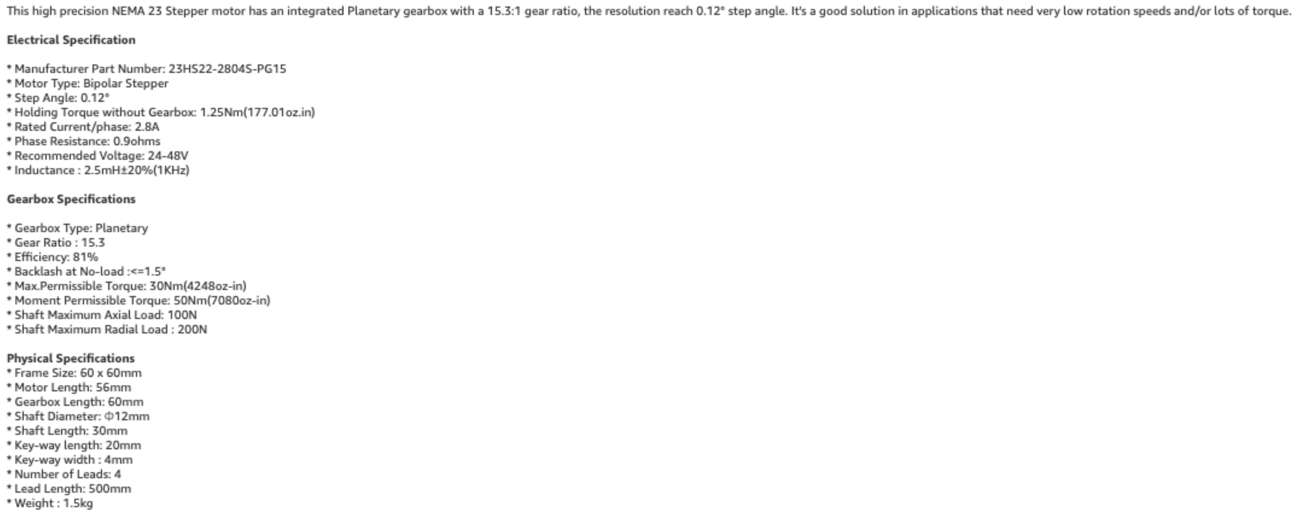
Conclusions:

The maximum motor torque required to drive the auger screw was determined to be approximately 9 N*m. An additional component selection criteria for the motor was that fine tuning of a low angular velocity was required (less than 20 rpm is expected). With both the relatively large torque requirement and the necessity for precise angular velocity control, a stepper motor with a gearbox seemed to be the best selection. Figures 21 and 22 show the final motor selected.



STEPPERONLINE 15:1
Planetary Gearbox Nema 23
Stepper Motor 2.8A for DIY
CNC Mill Lathe Router

Figure 21: Nema 23 Stepper Motor with 15:1 Planetary Gearbox



This high precision NEMA 23 Stepper motor has an integrated Planetary gearbox with a 15.3:1 gear ratio, the resolution reach 0.12° step angle. It's a good solution in applications that need very low rotation speeds and/or lots of torque.

Electrical Specification

* Manufacturer Part Number: 23HS22-2804S-PG15
* Motor Type: Bipolar Stepper
* Step Angle: 0.12°
* Holding Torque without Gearbox: 1.25Nm(177.01oz.in)
* Rated Current/phase: 2.8A
* Phase Resistance: 0.9ohms
* Recommended Voltage: 24-48V
* Inductance : 2.5mH±20%(1KHz)

Gearbox Specifications

* Gearbox Type: Planetary
* Gear Ratio : 15.3
* Efficiency: 81%
* Backlash at No-load :<=1.5°
* Max.Permissible Torque: 30Nm(4248oz-in)
* Moment Permissible Torque: 50Nm(7080oz-in)
* Shaft Maximum Axial Load: 100N
* Shaft Maximum Radial Load : 200N

Physical Specifications
* Frame Size: 60 x 60mm
* Motor Length: 56mm
* Gearbox Length: 60mm
* Shaft Diameter: Φ12mm
* Shaft Length: 30mm
* Key-way length: 20mm
* Key-way width : 4mm
* Number of Leads: 4
* Lead Length: 500mm
* Weight : 1.5kg

Figure 22: Motor and Gearbox Specifications

Figure 23 indicates typical motor loads from the simulation data.

Integral Parameter	Value	X-component	Y-component	Z-component
Force [N]	78.074	9.533	2.660	77.444
Torque [N*m]	15.702	6.909	14.033	-1.370
Torque of Friction Force [N*m]	0.154	0.113	-0.060	0.086

Figure 23: Typical Loads on Motor from Simulation

By reviewing Figures 21-23, it is evident that the selected motor will easily withstand the expected loads. It is important to note that the maximum torque of the motor with the gearbox is 30 N*m, this is over three times the expected maximum torque required from the simulation data. This drastic oversizing is partly due to ensuring robustness and durability of the design, but also because the cost of the motor is relatively inexpensive, at just $70.