Simplified model of regeneratively cooled rocket nozzle – a SolidWorks project

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I chose to model a section of a rocket engine, a converging-diverging nozzle, also known as the 'de Laval' nozzle.

Principles of operation of this deceivingly simple device are quite complex. It's a perfect subject for various simulations (mechanical stress, fluid flow, temperature influence) and I perform a few simple ones inside SolidWorks at the end of the project (as much as the power of the computer allowed).

There are many fascinating subjects to explore, like the behaviour of the fluids flowing through the nozzle at supersonic speeds and their relation to chamber pressure, pressure at the exit etc.

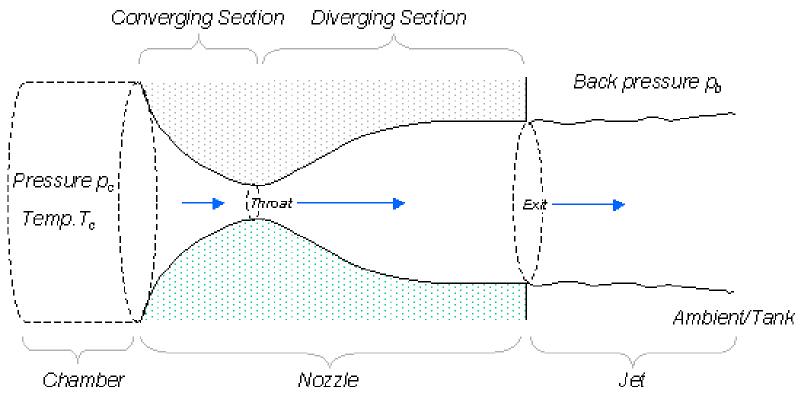

Fig. 1. Diagram of a converging-diverging nozzle.

The inspiration came from recent developments in additive manufacturing of rocket nozzles at NASA, more specifically for coolant channel closeout. A new Laser Wire Direct Closeout (LWDC) capability reduces the time to fabricate the nozzle.[1]

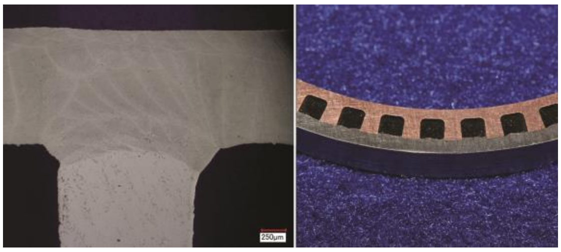

Fig. 2. Quality of the bond at the interface; a copper channel closed out with stainless.

[1] https://technology.nasa.gov/patent/MFS-TOPS-81

Regenerative cooling is a method of cooling the engine by flowing some of the propellant through channels around the combustion chamber. For example, SpaceX Raptor engine uses milled copper channels with an inconel jacket. Peak pressure in regen chamber is far above combustion pressure at over 800 bar or ~12,000 psi.[2]

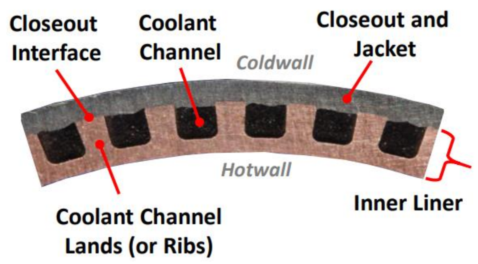

Fig. 3. Channel wall cross section.

There are even more recent additive manufacturing (AM) technology developments, for example a patented Aluminum 6061-RAM2 alloy allows for aluminum alloys to be printed using various AM techniques and at various scales.[3]

Techniques like this could have applications in other industries – e.g. oil, gas and nuclear power (heat exchangers).[4]

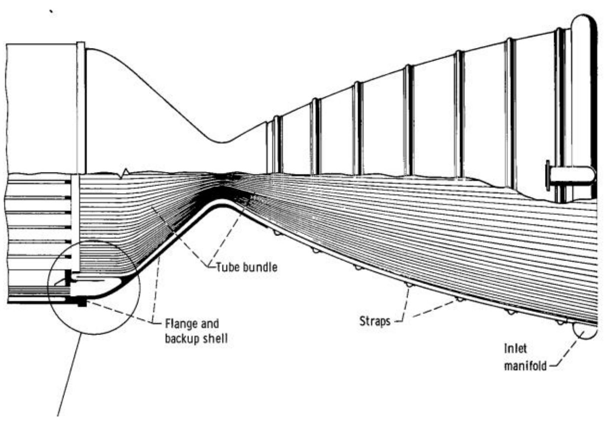

Fig. 4. A diagram used for tracing the nozzle in my SolidWorks model (from a 1966 paper titled 'A design study of a regeneratively cooled nozzle for a tungsten water-moderated nuclear rocket system').[5]

[2] https://x.com/elonmusk/status/1177387141116002304
[3] https://ntrs.nasa.gov/citations/20230009166
[4] https://technology.nasa.gov/patent/MFS-TOPS-81
[5] https://ntrs.nasa.gov/api/citations/19670004203/downloads/19670004203.pdf

Creating the part

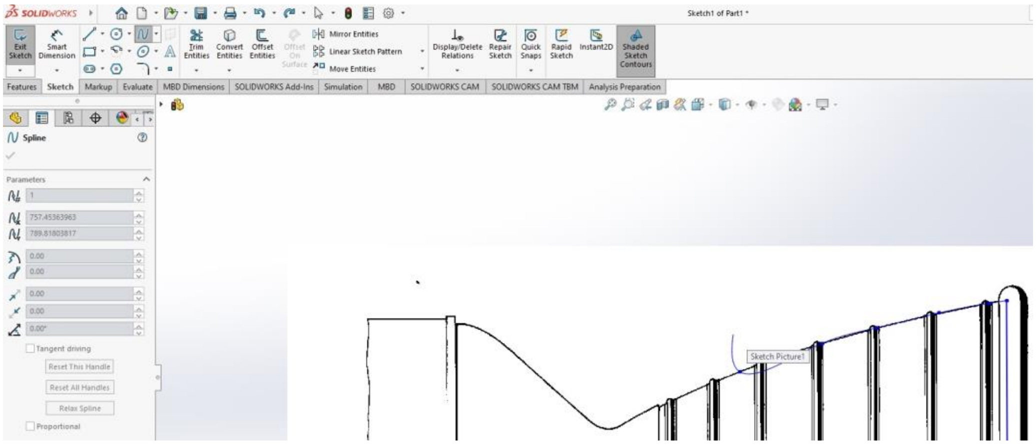

Fig. 5. Tracing with the spline tool.

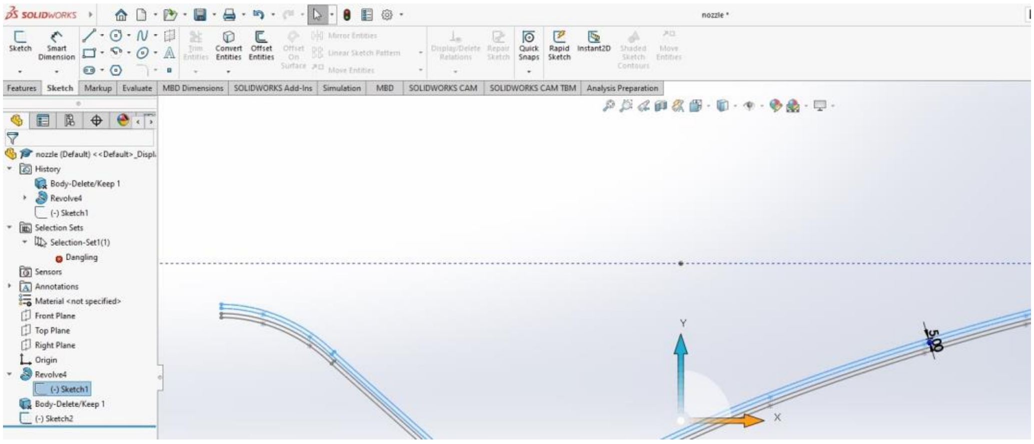

Fig. 6. Copying shapes to create walls and channels.

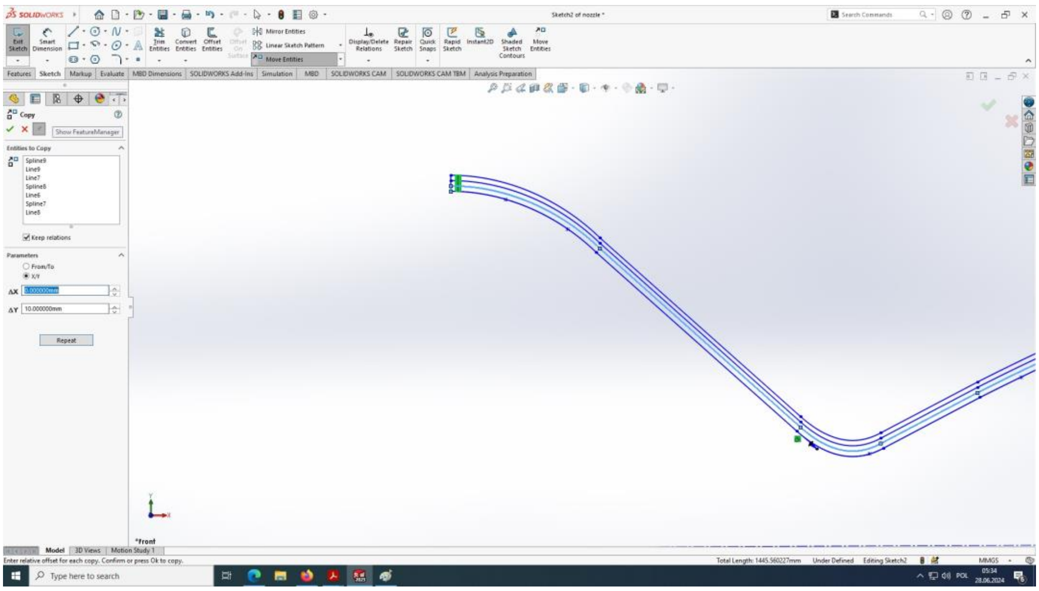

Fig. 7. Adjusting the distances.

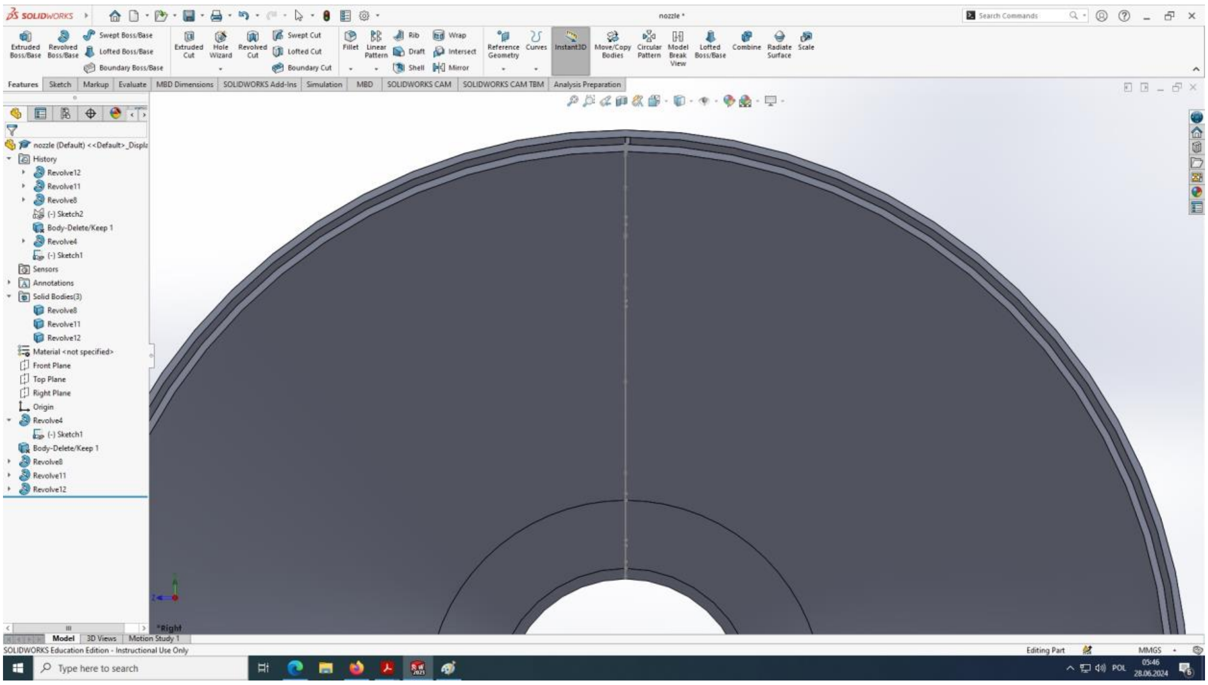

Fig. 8. Using the revolve tool.

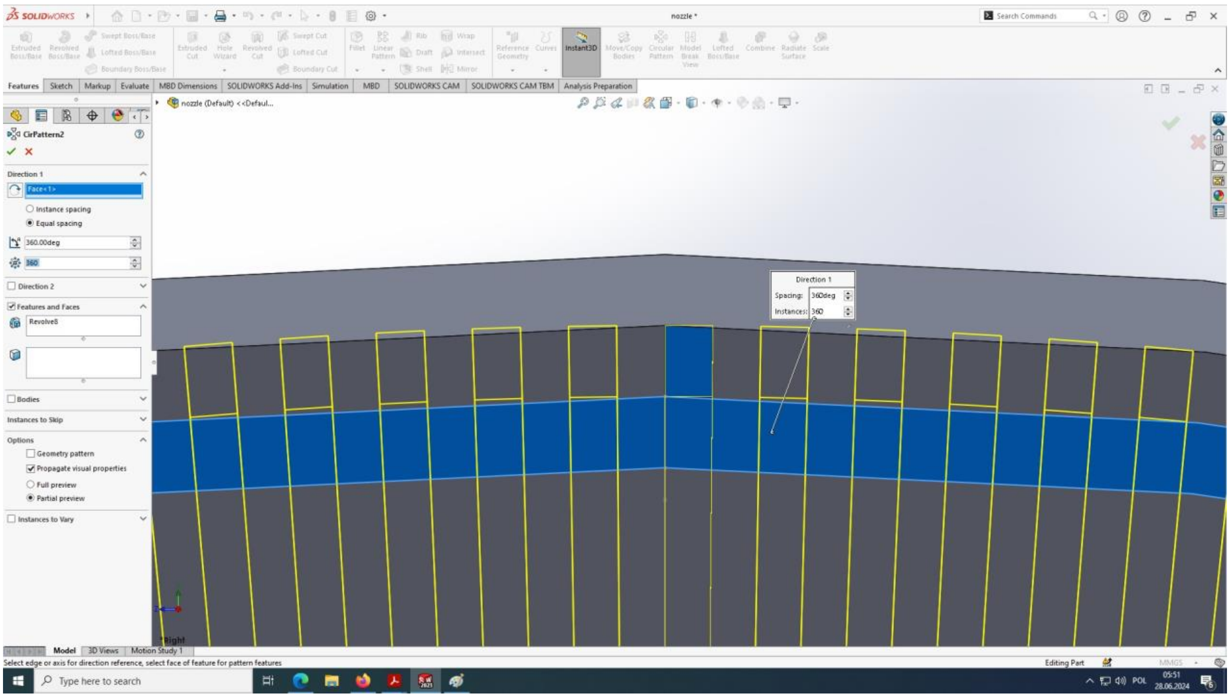

Fig. 9. Creating a circular pattern of channel walls.

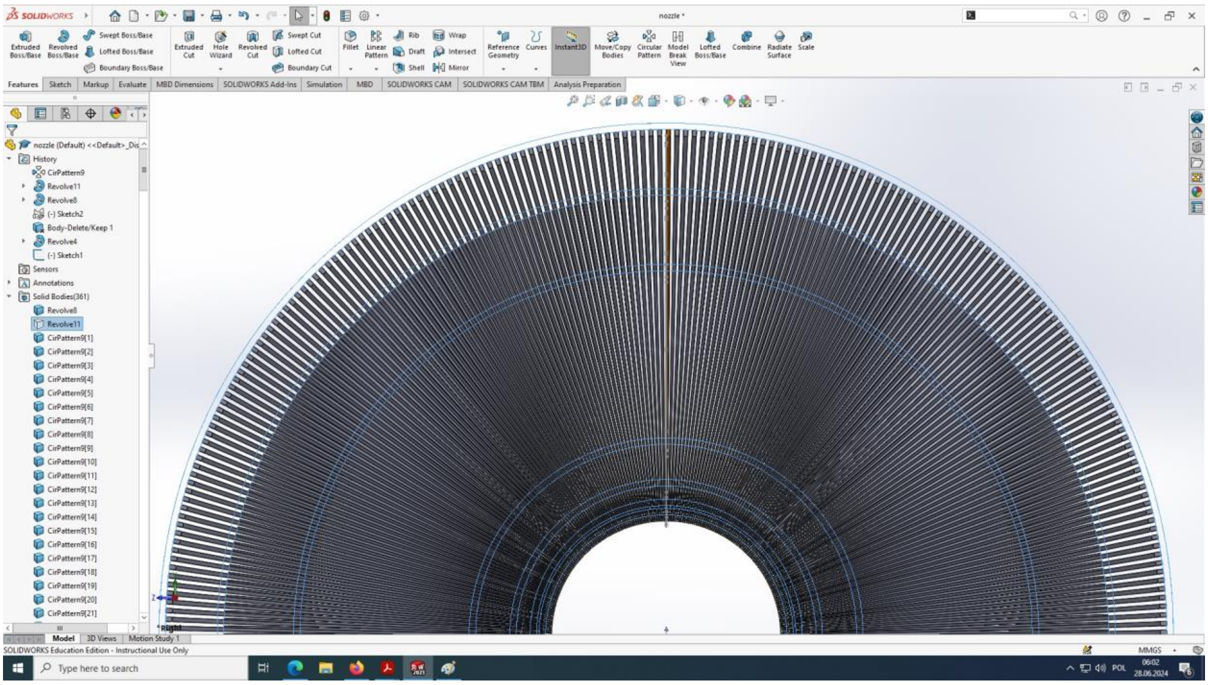

Fig. 10. Process of generating the channels.

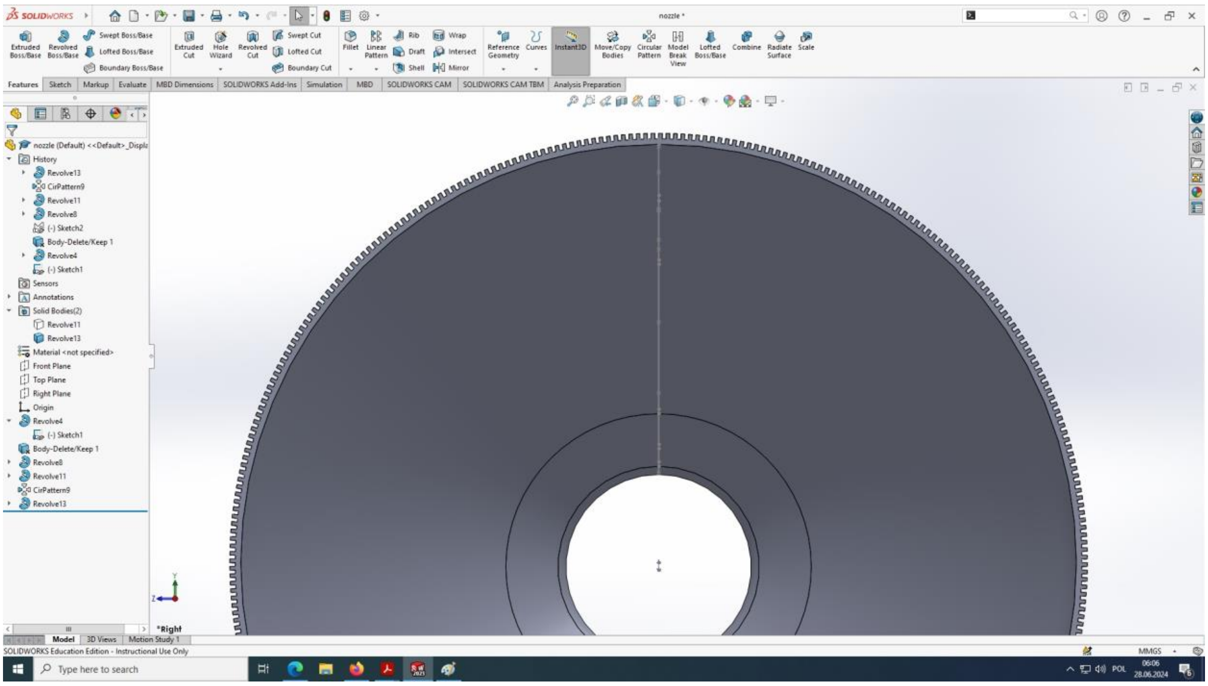

Fig. 11. Combining the walls with channels.

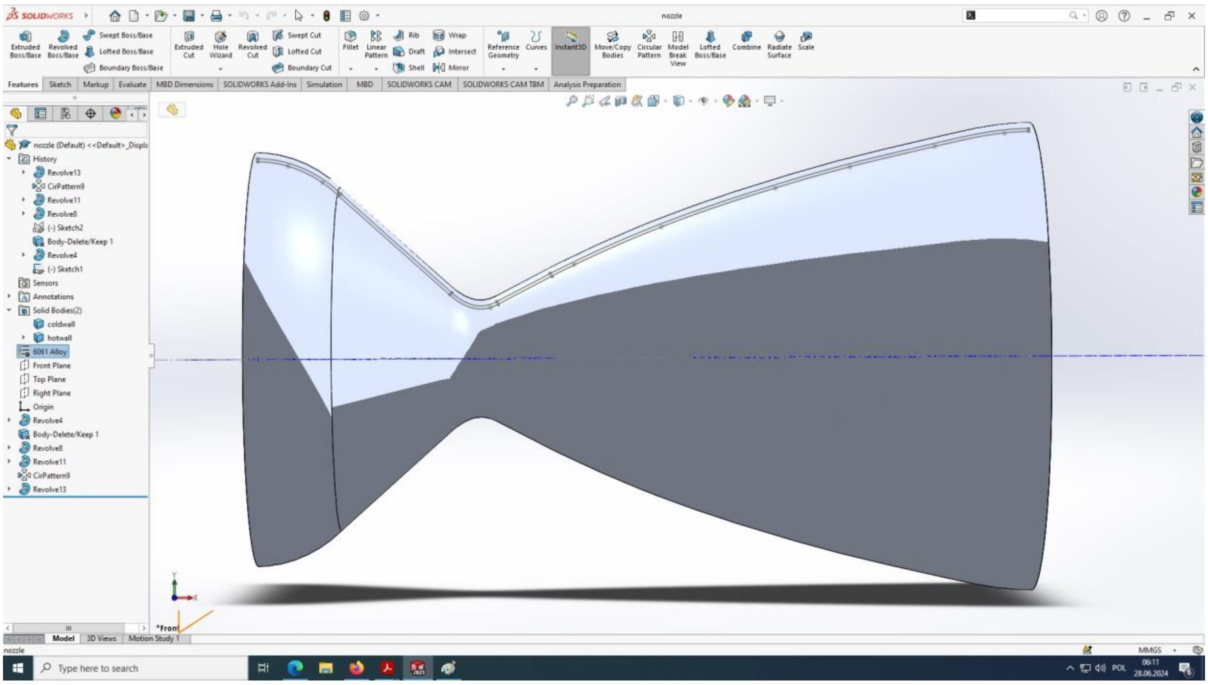

Fig. 12. Choosing the materials.

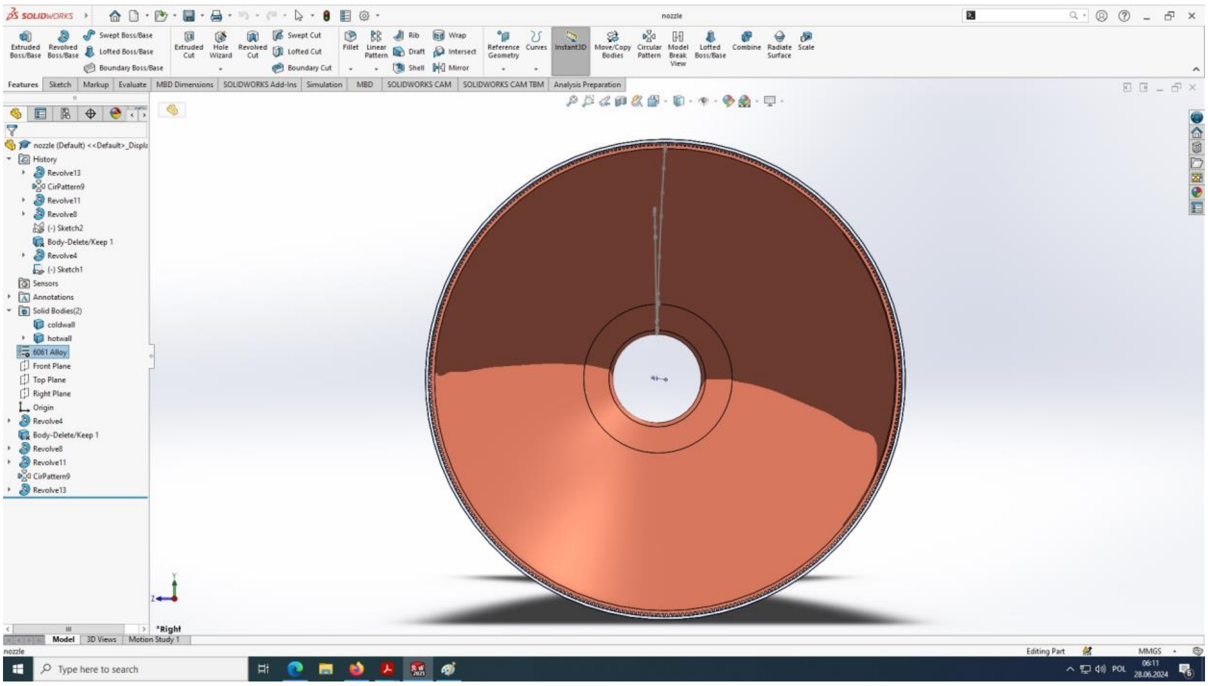

Fig. 13. Copper for the inner wall.

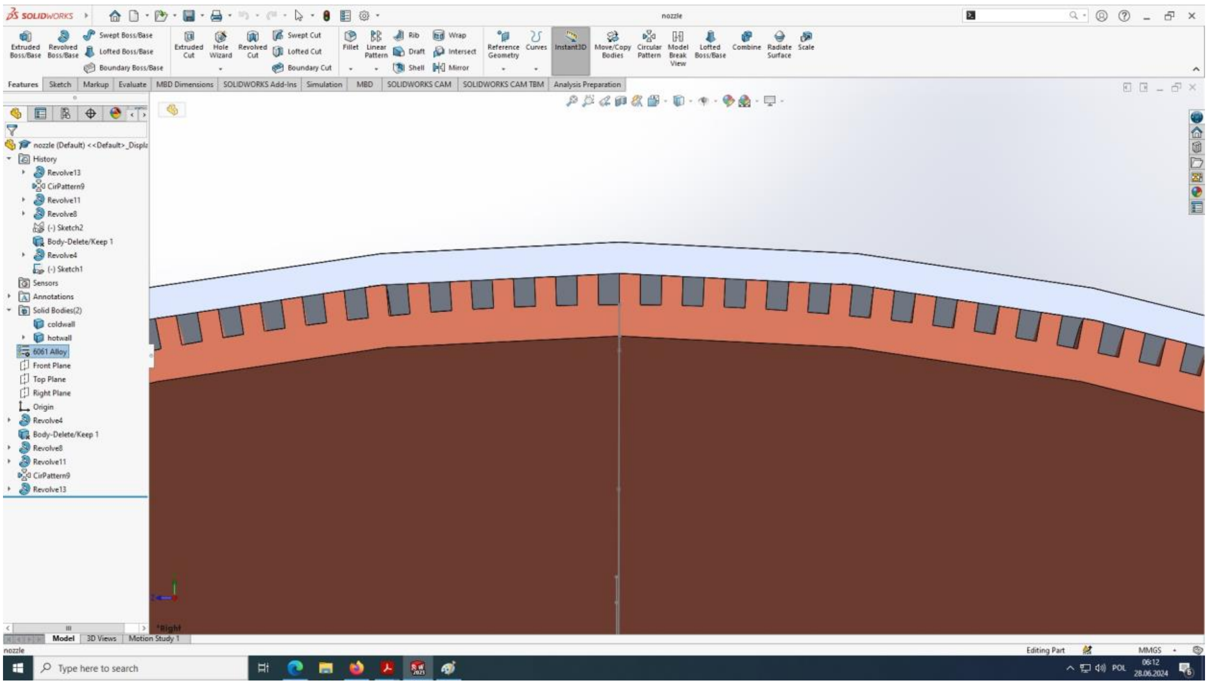

Fig. 14. Close-up view.

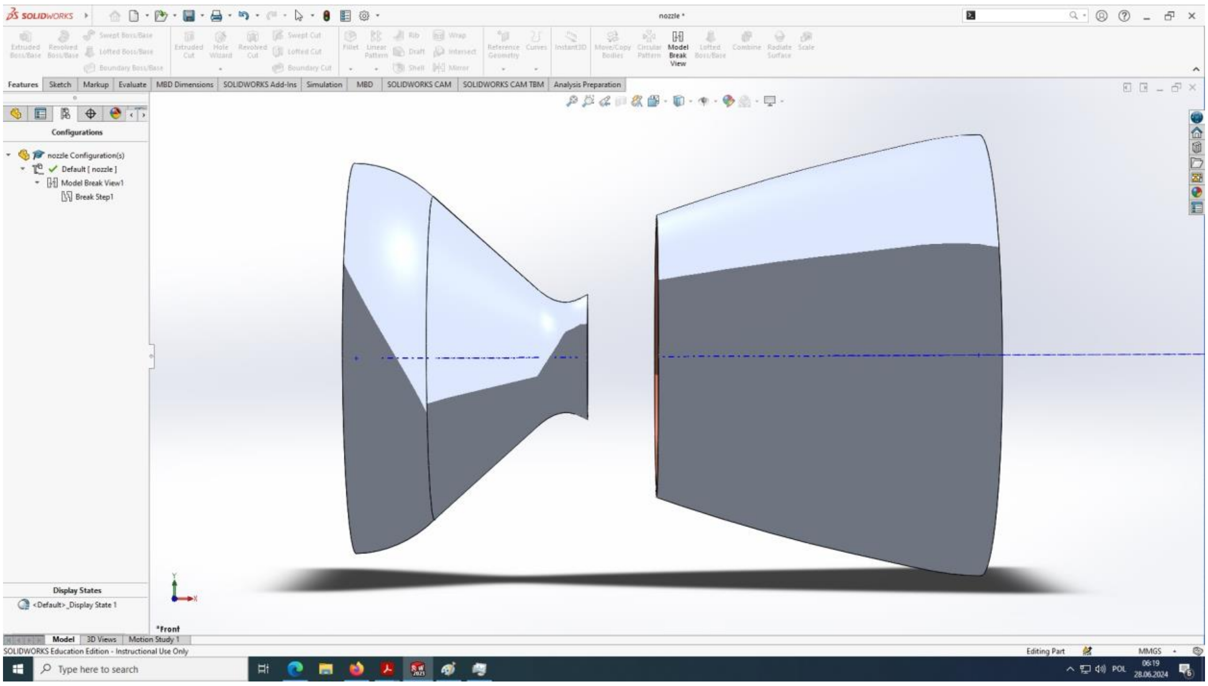

Fig. 15. Trying the Model Break feature.

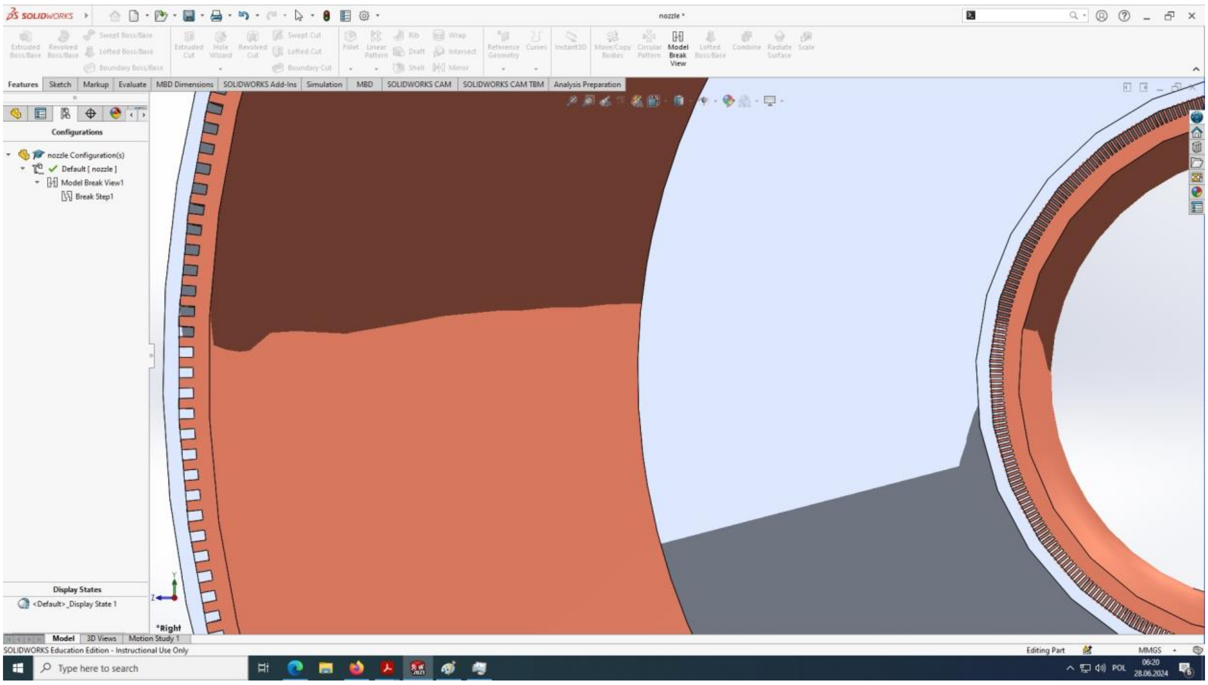

Fig. 16. Demonstrating appropriate scaling of channel walls at the entire length of the nozzle.

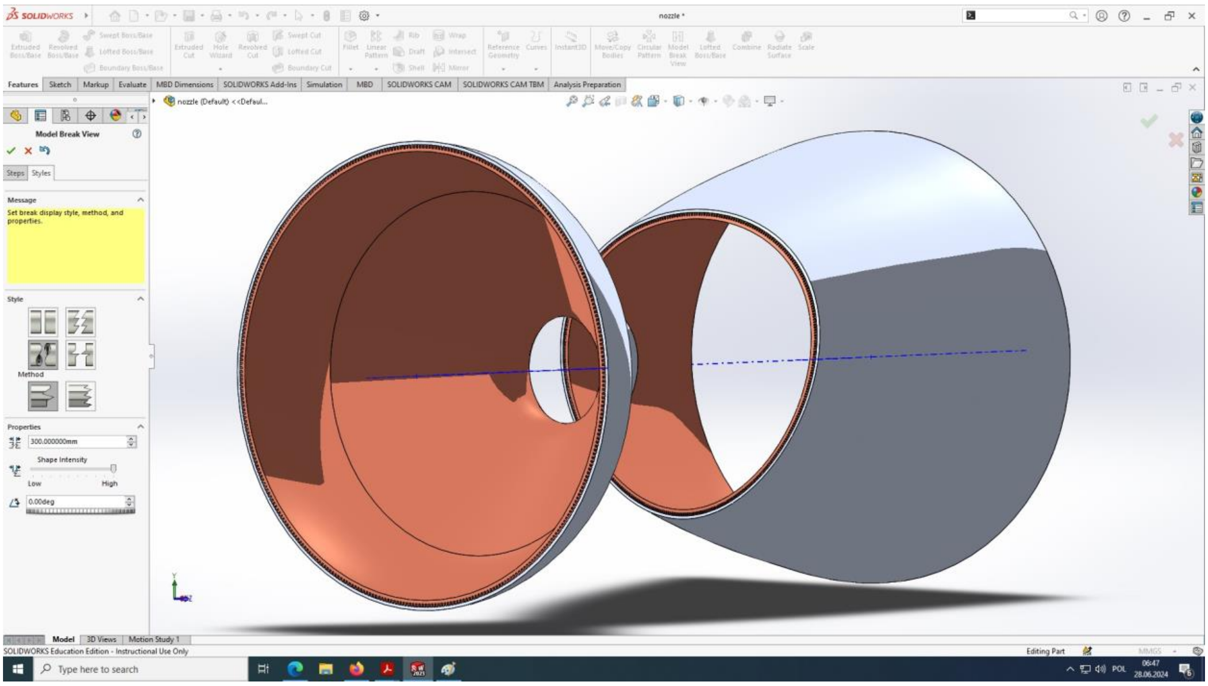

Fig. 17. Perspective view of the broken-up nozzle.

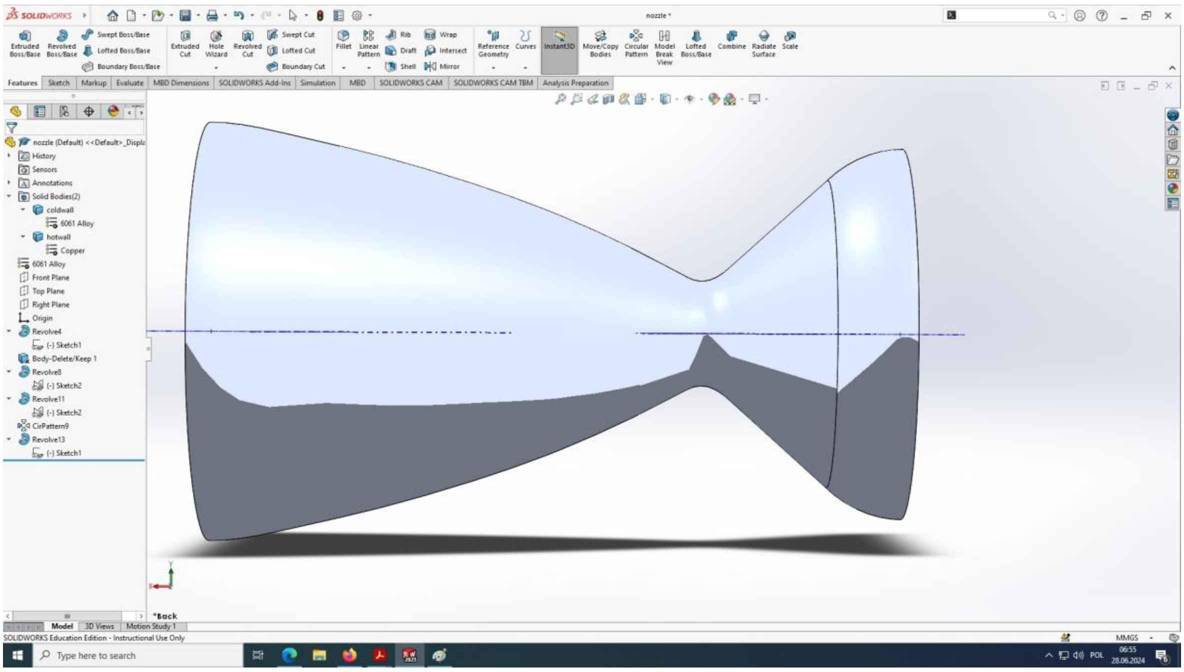

Fig. 18. Side view.

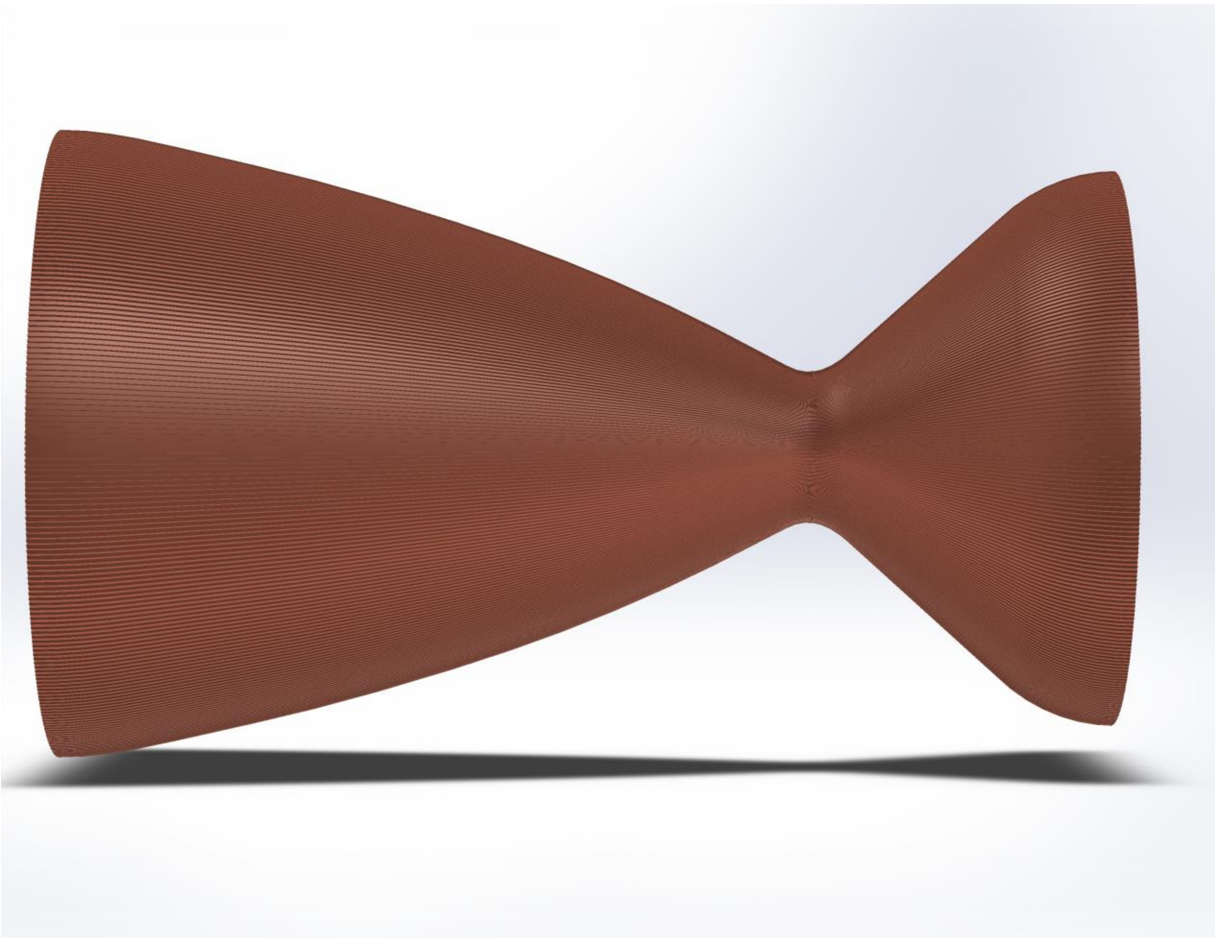
Fig. 19. Side view with the outer wall invisible (showing the channels).

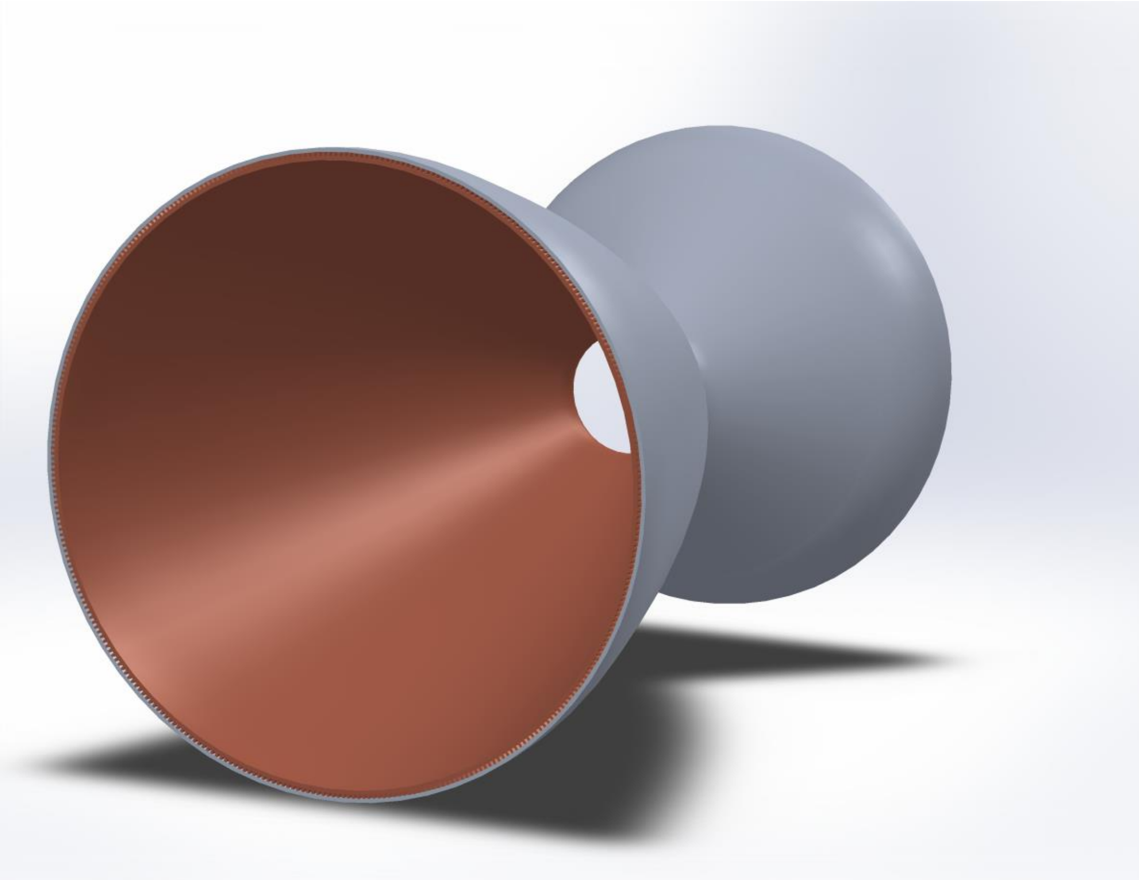

Fig.

Fig. 20. High resolution render from SolidWorks export (print) feature.

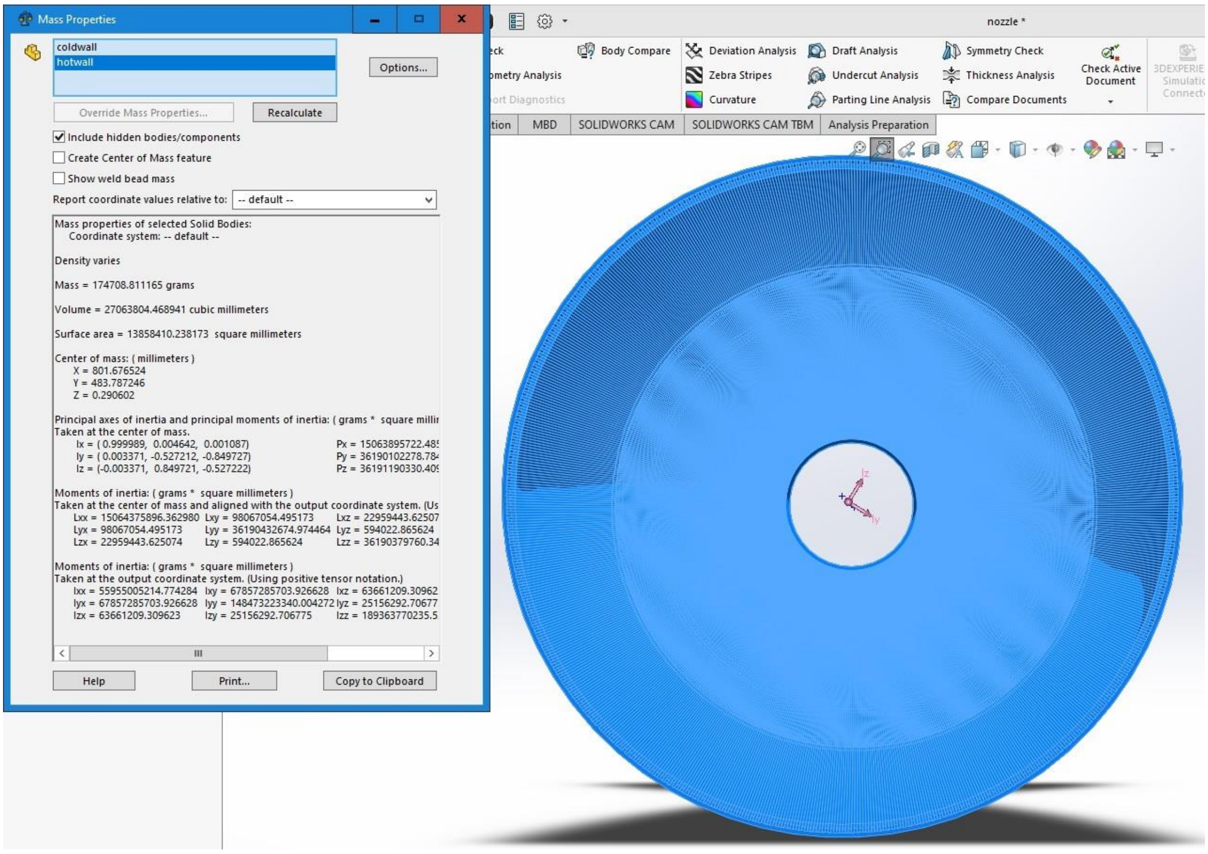

Fig. 21. Generating the report for Mass Properties (total mass: ~174kg).

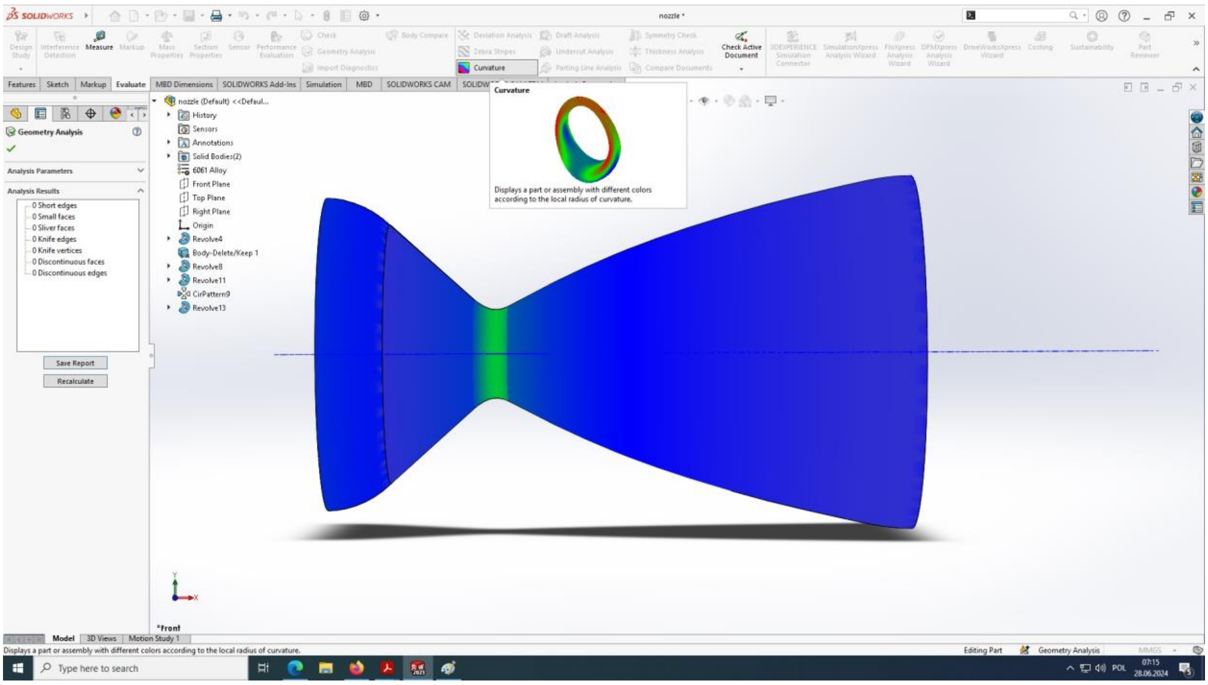

Fig. 22. Geometry (curvature) analysis.

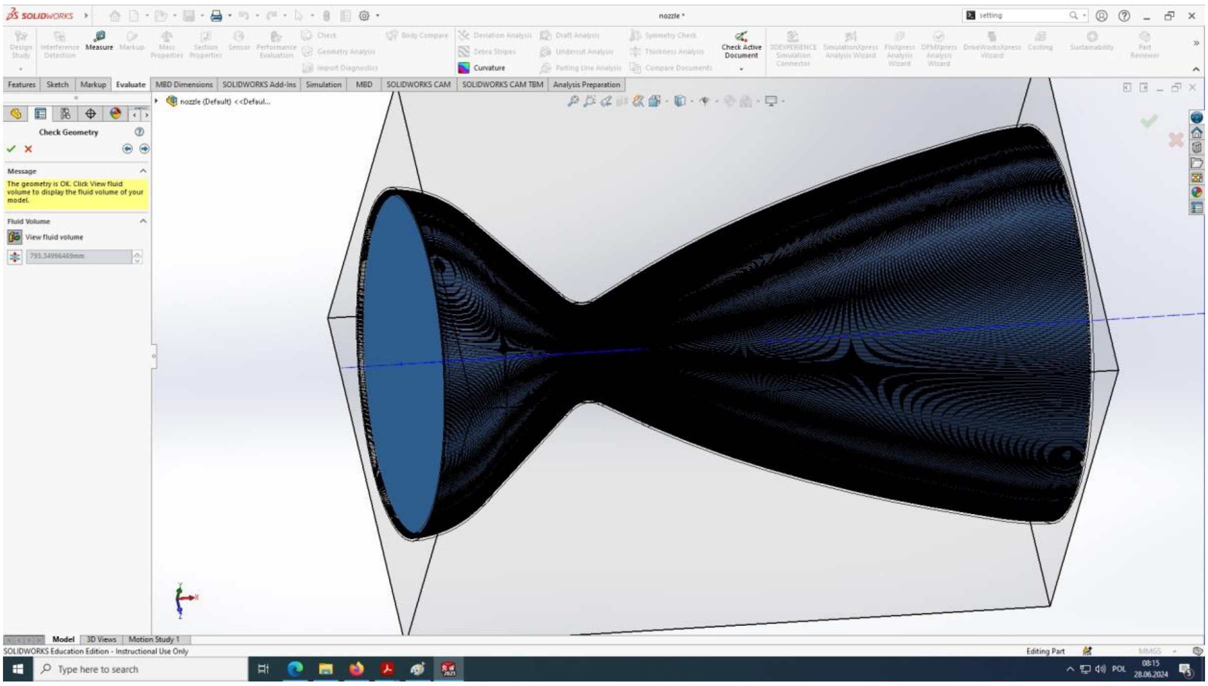

Fig. 23. Checking the fluid volume.

Setting up a fluid simulation (SOLIDWORKS FloXpress)

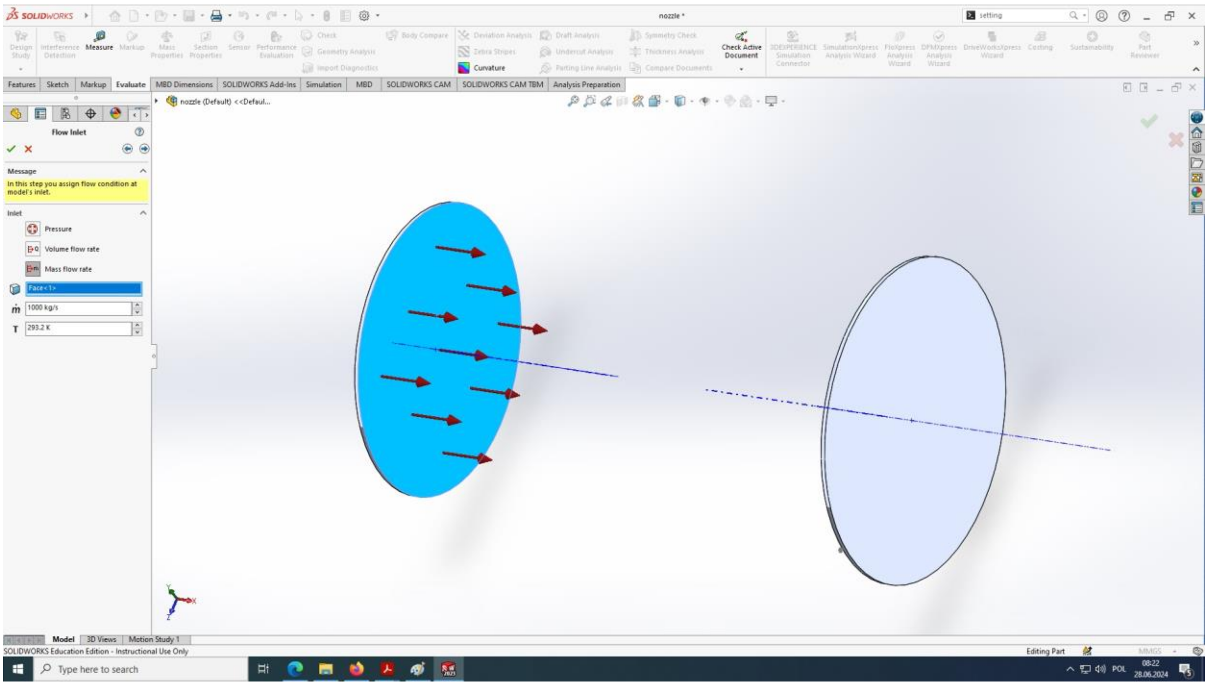

Fig. 24. Fluid sim required creating lids for inlet and outlet.

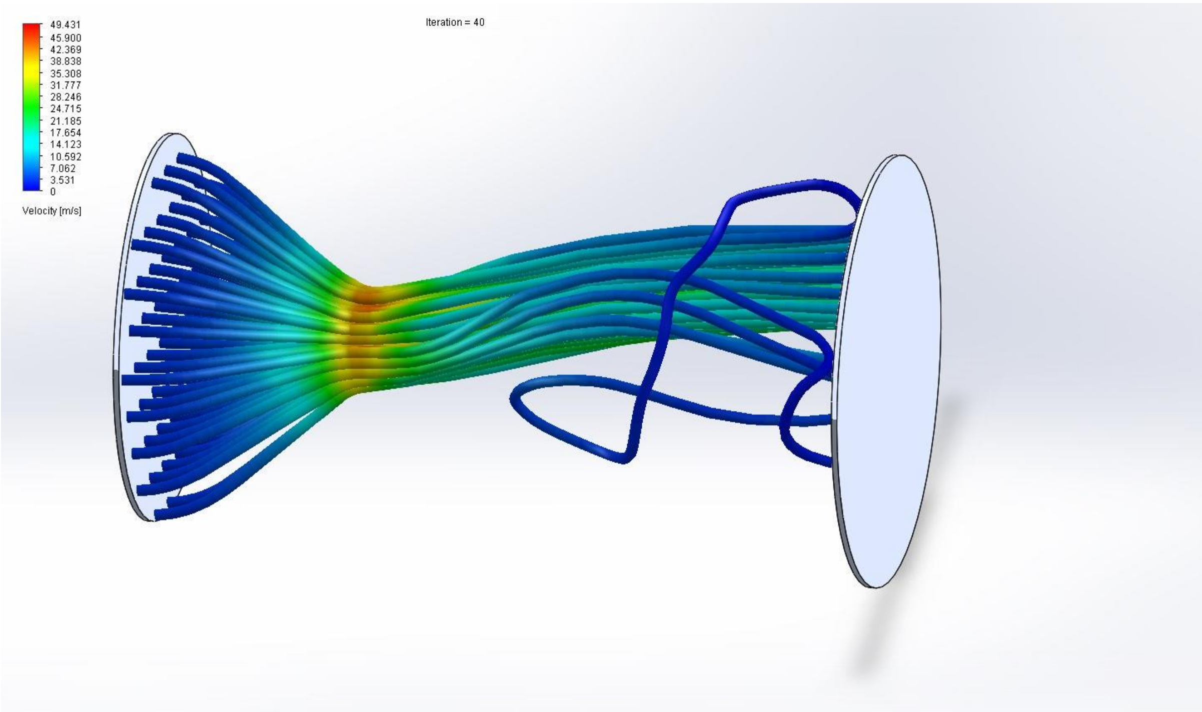

Fig. 25. The simulation shows unexpected behaviour (flow diverging in one direction).

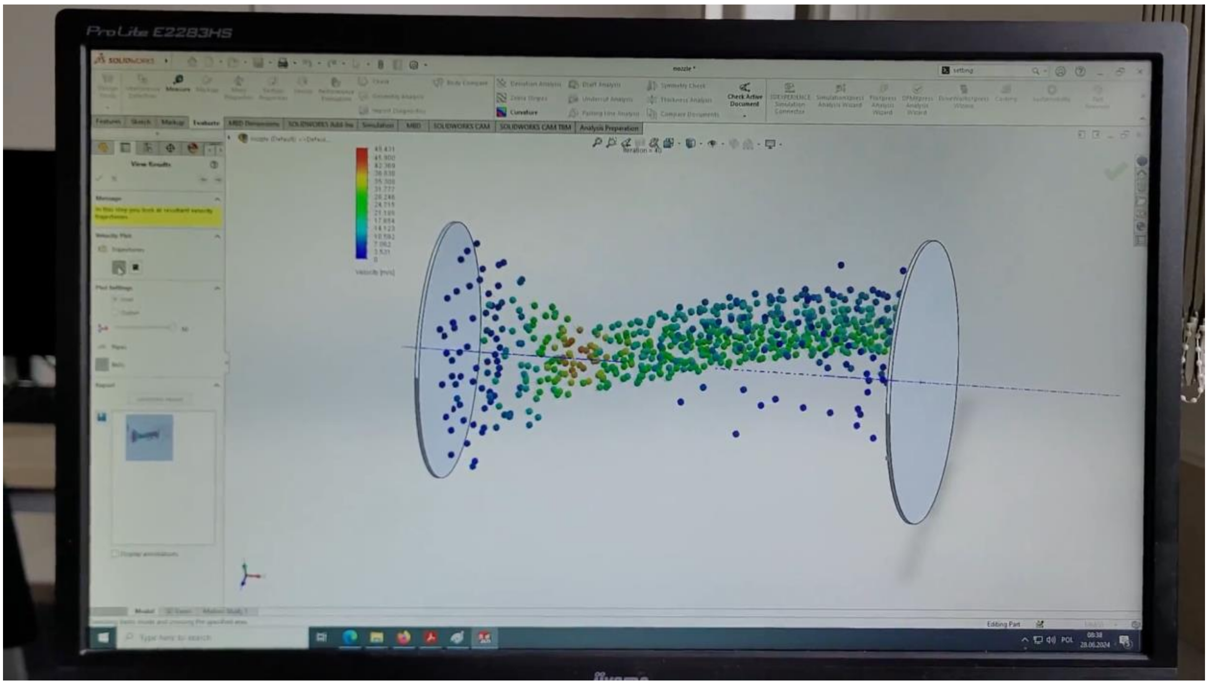

Fig. 26. The throat of the nozzle increases the fluid velocity as expected.

Conclusions

Creating the model in SolidWorks proved to be a fascinating task and allowed me to learn all the basic features of the program. More work and a better PC is necessary for more interesting simulations, but I'd like to explore them further. However, quick features like geometry verification and Mass Properties seem very useful. I tried using the Cost Check function (since I used real materials – copper and aluminum), but it made the program crash.

References

1. Puthoff, Richard L. *A Design Study of a Regeneratively Cooled Nozzle for a Tungsten Water-moderated Nuclear Rocket System*. National Aeronautics and Space Administration, 1966.
2. Gradl, Paul R., and Christopher S. Protz. "Channel wall nozzle manufacturing technology advancements for liquid rocket engines." *International Astronautical Congress (IAC), 2019*. No. M19-7683. 2019.
3. Gradl, Paul R. "Rapid fabrication techniques for liquid rocket channel wall nozzles." *52nd AIAA/SAE/ASEE Joint Propulsion Conference*. 2016.
4. Fagherazzi, Matteo, et al. "A Simplified Thermal Analysis Model for Regeneratively Cooled Rocket Engine Thrust Chambers and Its Calibration with Experimental Data." *Aerospace* 10.5 (2023): 403.
5. Fedotowsky, Tessa M., and Benjamin B. Williams. "Reactive Additive Manufacturing for Fourth Industrial Revolution Exploration Systems (Ramfire) Aluminum 6061-Ram2 Nozzle Testing." *Marshall Space Flight Center Jamboree & Poster Expo*. 2023.