Simulation of a Downsized FDM Nozzle

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Abstract: This document discusses the simulation of a downsized nozzle for fused deposition modelling (FDM), namely the E3D HotEnd Extruder with manufactured diameters of 200-400 µm in the nozzle tip. The nozzle has been simulated in terms of heat transfer and fluid flow giving an insight into the physical behavior of the polymer inside the nozzle.
The extruder contains a nozzle, a heater block, a heatbreak and a heatsink additionally cooled by a fan. The diameter is located in the sub-mm region allowing to reduce the size and surface roughness of the product.
The simulation results were experimentally validated. This kind of simulations is facing multiple problems connected to the description of the material properties with temperature and pressure dependency.

Keywords: additive manufacturing technology, fused deposition modelling, rapid prototyping, heat transfer, fluid flow.

1. Introduction

Fused deposition modelling (FDM) was originally introduced in the 1980s, but is still suffering from a lack of surface quality. There have been several approaches on improving especially surface roughness. Multiple sources, e.g., Anitha et al. 2001 [1] considered the following parameters important for the product quality:

- layer thickness
- road width
- speed

Especially in terms of the first two items, the size of the nozzle has a significant influence. The current paper discusses the surface control during the manufacturing process. Other papers, e.g., Galantucci et al. 2009 [2] and P.M. Pandey et al. 2003 [3] reported the improvement of the surface quality by chemical finishing or hot cutter machining.

For this paper, simulations on an E3D HotEnd extruder nozzle with different diameters in multiple configurations. In order to perform this, a COMSOL model was generated discussing the heat transfer within the nozzle, as well as the fluid flow of the polymer in a pressure-dependent environment.

Additionally, the simulation results were validated in physical experiments, which are described in detail in Hofstaetter 2015. Some material parameters, such as viscosity and the overall heat transfer coefficient were adapted with experimental data as described later on.

2. COMSOL Multiphysics Modelling

The model is fed with data from the material database included in COMSOL Multiphysics as well as individually generated data from experiments and literature. The model contains the entire nozzle design including heating and cooling elements simulating the entire process from electric heating to thermal conduction. The model includes two solvers:

- heat transfer (in solids/fluids)
- laminar flow

2.1 Implementation

The geometry of the model is described by a CAD model based on the geometries of the original E3D HotEnd extruder. The model consists of

- a nozzle (brass),
- a heater block (aluminum),
- a heatbreak (steel),
- a heatsink (aluminum) and
- an additional fan.

The geometry is imported from a CAD model as shown in figure 1, while the fan is simulated by a block located around the heatsink attached with a constant airflow.

The feed is supposed to be performed outside the extruder by a linear stepper motor applying a pressure on the filament fed into the extruder.

All elements are physically (and especially thermally) connected by threads and allow heat transfer across their borders.

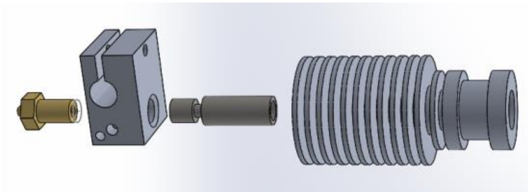

Figure 1. E3D HotEnd extruder

2.2 Material

Material properties for aluminum, brass and steel were summarized from literature by Hofstaetter 2015 [4] based on SI Metric 2015 [5] as well as the COMSOL Multiphysics material data base:

Aluminum	
Density	2700 kg/m³
Thermal conductivity	238 W/(mK)
Heat capacity	900 J/(kgK)
Stainless steel	
Density	7850 kg/m³
Thermal conductivity	44.5 W/(mK)
Heat capacity	475 J/(kgK)
Brass	
Density	8525 kg/m³
Thermal conductivity	109 W/(mK)
Heat capacity	377 J/(kgK)

The values for the air flow were taken from the COMSOL Multiphysics material data base and are temperature dependent.

Besides the above mentioned metals and air, the model uses acrylonitrile butadiene styrene (ABS) with a constant density of 1040 kg/m³, a constant thermal conductivity of 0.18 W/(mK) and a constant heat capacity of 1847 J/(kgK). The polymer fluid above glass transition temperature is assumed to be inclompressible. The viscosity is non-linear and based on the linear Cross-WLF model of Shin et al. 2013 [6]. Viscosity is exponentially dependent respectively on the shear rate as well as the temperature by the form of

$$\eta(T,\dot{\gamma}) = \frac{\eta_0(T)}{1+(\eta_0(T)\dot{\gamma}/\tau)^{1-n}}$$

$$\eta_0(T) = D_1 \exp\left[\frac{-A_1(T-T_r)}{A_2+(T-T_r)}\right]$$

with the coefficients published for ABS by Shin et al. 2013 [6] and experimentally validated by Hofstaetter 2015 [4]:

$$\tau = 3.48\times 10^4\,\mathrm{Pa}$$
$$n = 0.289$$
$$D_1 = 8.62\times 10^{11}\,\mathrm{Pa\,s}$$
$$T_r = 373.15\,\mathrm{K}$$
$$A_1 = 24.96$$
$$A_2 = 51.6\,\mathrm{K}$$

Figure 2 shows the temperature dependence as well as the shear dependence of the Cross-WLF model. The model has also been experimentally validated by Yang 1999 [7].

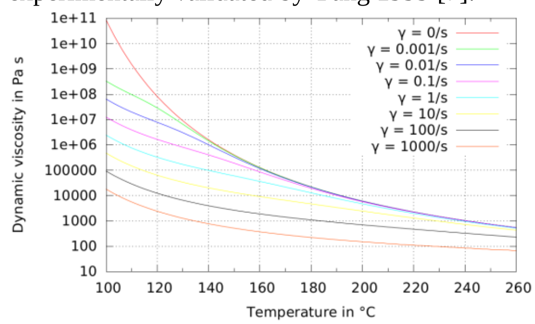

Figure 2. Viscosity of ABS over temperature according to the linear Cross-WLF model, Shin et al. 2013 [6]

2.3 Heating and Cooling

Heat transfer in the COMSOL Multiphysics module for heat transfer in solids and fluids is governed by the heat transfer equation

$$\rho C_p \mathbf{u}\cdot\nabla T = \nabla\cdot(k\nabla T) + Q$$

Heating is performed by an electric heating device, which – in reality – is powered by 25 W. Experiments concluded, that in order to reach a suitable printing temperature for ABS of 230 °C, heating of 15 W leads to the aimed stationary temperature in the nozzle tip. As a consequence, the heating power is only completely turned on during heating up the nozzle from room temperature.

Using the COMSOL Multiphysics module for heat transfer in solids/fluids, the heat is transferred through the model. A constant overall heat transfer coefficient of 15 W/(m²K) is assumed based on data from The Engineering toolbox (2015) [8] stating values between 7 and 35 W/(m²K) and experiments showing that this value is suitable for the laboratory environment.

Environment temperature was assumed as 20 °C and has a major influence for the cooling effect of the fan. It is simulated using the heat transfer in fluids module. The block, placed around the heat sink has the dimensions of 30x30x60 mm³. The air enters the control volume on the front side with a constant velocity of 2550 mm/s. This value is similar to reality for usual fans for this task.

2.4 Fluid flow

Laminar flow in the COMSOL Multiphysics module is governed by the Navier-Stokes equation

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + \eta\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right) - \frac{2}{3}\eta(\nabla\cdot\mathbf{u})\mathbf{I}\right] + \mathbf{F}$$

$$\nabla\cdot(\rho\mathbf{u}) = 0$$

In the extruder, ABS starts melting as soon as glass transition temperature is reached in the heatbreak right before entering the nozzle. From this point on, the fluid flow is simulated. The flow is forced by a pressure difference between the inlet and the outlet at the nozzle tip. The flow is assumed to be laminar within the nozzle due to the low Reynolds-number (caused by the low diameter and high viscosity respectively).

Pressure difference is analyzed by a parameter sweep between the values of 3 atm and 12 atm with a step size of 3 atm. Outlet pressure is set to a constant value of 1 atm. It was shown by Andersen 2015 [9] for PLA and Hofstaetter 2015 [4] for ABS that common stepper motors for polymer extrusion are limited in terms of feed velocity of the original filament. Nevertheless, there is a range allowing adaption of printing velocity. Hofstaetter 2015 [4] showed in experiments, that the standard linear stepper motor SY 4 2STH38-1684A underlies a nearly linear slippage before the feed of 100 mm/min on a 1.75 mm ABS filament.

3. Results and Discussion

3.1 Heat distribution

Heat distribution shows a significant gradient from the nozzle to the heatsink. This gradient is especially distinct in the region of the heatbreak showing its functionality as an isolator. This fact allows the polymer to melt quickly and prevent degradation in the nozzle due to long heated periods.

Stationary temperature with 25 W heating is reached after less than 600 s shown in figure 3.

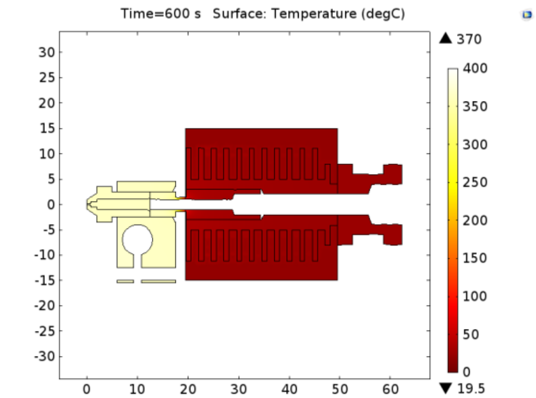

Figure 3. Heat distribution in the nozzle after 600 s of heating with 25 W

Note the nearly isotropic heat distribution in the heater block and the nozzle due to the good heat conductivity whereas the heatbreak consists out of steel and therefore has a bad conduction.

The heating of the nozzle from room temperature of 20 °C to stationary temperature is shown in figure 4. The figure also shows averaged experimental results by Hofstaetter 2015 [4] with an average standard deviation of 0.15 °C.

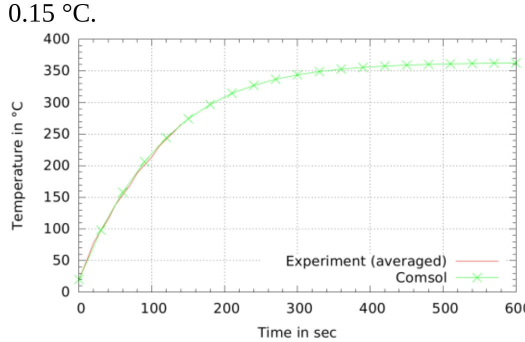

Figure 4. Heating process of the nozzle with 25 W heating and 15 W/(m²K) overall heat transfer coefficient.

These measurements and simulations were performed without fluid flow and measured close to the actual position of the thermistor in the E3D HotEnd extruder. It nevertheless showed up that the influence of the polymer flow through the nozzle has little impact on the temperature distribution in the range of 1/10°C. This mainly is caused by two reasons:

1. The heater is not running at full power and therefore can regulate the temperature to a given value by adapting the power inlet.
2. Andersen et al. 2015 and Hofstaetter 2015 showed, that the feed with a regular stepper motor with rollers is limited. Hence, the mass flow of material is also limited. Due to

the low heat capacity in the nozzle, the cooling effect during extrusion is reduced.

3.2 Fluid flow

Figure 5 shows the flow velocity in the nozzle tip close to the outlet of a 350 µm diameter nozzle. The fluid velocity in nozzle-direction shows a characteristic parabola form as would be supposed by the laws of fluid dynamics.

The velocity distribution is slightly asymmetric due to the asymmetric heat distribution caused by the position of the heating device in the heater block.

Values were calculated for pressure differences of 3, 6, 9 and 12 atm. The measurement in the simulation result is located 1 mm inside the nozzle at the outlet.

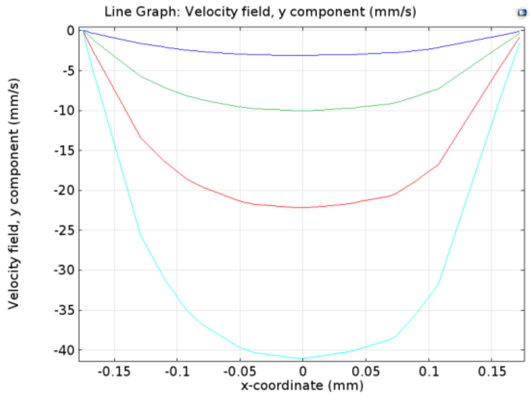

Figure 5. Pressure dependent flow velocity in the nozzle tip close to the outlet from 3 atm (violet) to 12 atm (cyan)

For interpretation reasons, the results were also plotted showing the velocity into the direction of the nozzle over the pressure difference. It appeared, that the velocity can be approximated with a one-parameter squared function. This fact is reasonably due to the Bernoulli equation. Figure 6 shows the velocity dependence on the pressure difference between inlet and outlet for the above mentioned pressure range.

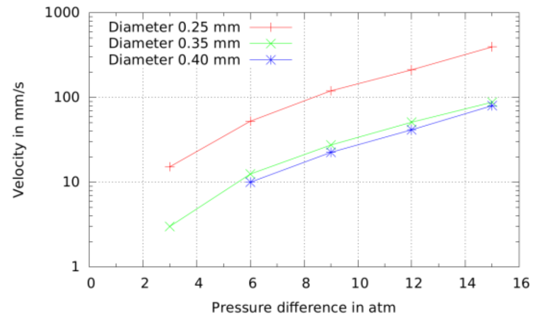

Figure 6. Velocity depending on the pressure difference with a quadratic function

4. Conclusions

The study is facing multiple tasks performed by COMSOL Multiphysics reaching from material science over heat transfer until fluid flow simulation.

Thus we conclude:

- A model of an E3D HotEnd extruder has been implemented and calibrated by experimental data.
- Simulation results give insight into the physical behavior and processes within the nozzle especially concerning velocity, viscosity and temperature.
- Heat distribution shows a characteristic gradient from the nozzle tip to the heatsink from 230 °C to 20 °C.
- The temperature gradient has a large change in the heatsink causing the polymer to melt quickly and prevent polymer degradation.
- Fluid flow is controlled by a pressure difference between the inlet and outlet causing a characteristic parabolic velocity distribution.
- Fluid velocity is quadratically depending on the pressure difference between inlet and outlet.

5. References

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