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THE INFLUENCE OF THE HEAT TRANSFER ON THE NOZZLE MADE FROM DIFFERENT MATERIALS FOR THE E3D VOLCANO SOLUTION

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ABSTRACT: The study aims on the 3D modelling on the E3D Volcano assembly and based on the Fused Deposition Modelling technology a thermal analysis is conducted on the nozzle made from different materials. The main objective is to simulate the loading conditions on the entire assembly focusing on using thermal convection and thermal radiation with different values for the steel, copper, brass convection coefficients as well as for the emissivity coefficients of the steel and aluminium. The thermal simulation will result into 3 levels of simulation each based on different materials used on the E3D Volcano assembly to determine the thermal gradients of each level individually. Although one of the parameters was eliminated, the power parameter [W] and it was replaced with the temperature parameter applied to the resistor with the value of 240 oC to observe the thermal behaviour on the loaded surfaces.

KEYWORDS: heat transfer, influence of materials, E3D Volcano nozzle, additive manufacturing, thermal simulation, data analysis

1. INTRODUCTION

3D Printing technology has been developing for many years and represents a continuous process of evolution of printing techniques. Regarding the fused deposition modelling known as the fused filament fabrications, this process belongs to the extrusion material branch. The development of 3D printing technology has enabled making prototypes as well as spare parts or complete devices with attractive properties, usually of small size. [1]

FDM technology is currently the most widespread way to rapid production of items utilizing additive manufacturing. [2, 14, 15]

Thermoplastic polymer materials are used in the industrial engineering industry, automotive industry, electronic industry even in medical system because the material has specific characteristics on melting procedures on the temperature and, they got specific solidification proprieties when the main process will take place in 3D printing. The assembly parts of the E3D Volcano also have material parts with specific thermal conductivity proprieties regarding the steel, aluminum, copper, and brass which will contribute on the study of the influence of the heat transfer on the printing nozzles made from different materials Figure 1.

Additive manufacturing known as 3D printing technology is using the CAD/CAM/CAE structure to create 3D printed parts layer by layer (starting from a base line and continuing by adding thin specific layers from the bottom to the top of the 3d part until the process is complete) on a specific flow rate of the filament on the E3D Volcano nozzle which involves a diameter of 0.2 mm.

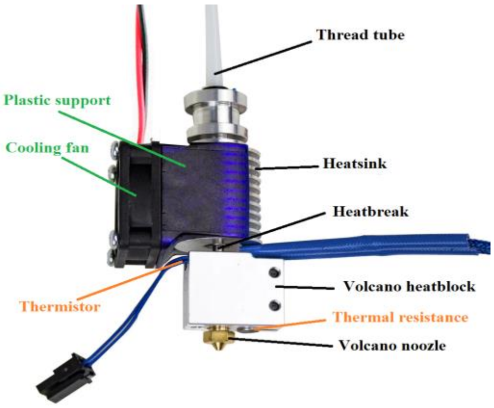

Figure 1. [12]

The process of additive manufacturing involves the E3D Volcano assembly described below:

- The main parts are the nozzle, heating block, thermal threaded separation tube, cooling block, plastic support, cooling fan and the 0.2 mm ABS wire.
- The ABS Plastic wire is inserted into the 3D printer and then from the display we will have to set up the main temperature values for the working table and for the nozzle, then the filament will start melting on a specific level of temperature (in this case temperature of the nozzle will be 240 ^{o}C.
- The process of extrusion of the material will take place from the nozzle to the working table regarding the specific 3D modelling part, in which the 3D printer will work on the 3-axis system (X, Y and Z directions) using thin hot layers which will cool down in the process of solidification to shape the 3D modelling part in its final form. [3]

The 3D printing process will be a repetitive process because when a layer of material is deposited, the working table will go down to make room for a new layer to be deposited (layer by layer process).

In present the technologies are using material extrusion process in a simple way, the material is forced through a well determined orifice nozzle with a specific diameter, at a specific or constant speed. The plastic material which is extruded through the nozzle hole must be in a phase of semi-solid to be deposited into layer by layer. [4]

2. THERMAL SIMULATION TO OBTAIN THE TEMPERATURE GRADIENTS OF THE NOZZLE MADE FROM DIFFERENT MATERIALS)

Running the 4 simulation each one by one for the E3D Volcano assembly can take time in the process of simulations due to iterations of the calculus and the computer resources will increase for the program to simulate a clean result at the end of the simulation. Autodesk Fusion 360 will be the main software for the thermal simulation. The analysis will be conducted by eliminating the power parameter from the thermal resistance and applying internal heat of 240 ^{o}C on the thermal resistance to supervise thermal behaviour during the process of the E3D Volcano assembly.

An experiment was conducted by an engineering team, using infrared thermometer on a sample of metal material which was in the state of cooling (from hot stage to cooling stage). From the investigations on the specific metal materials, a value regarding the convection coefficient was determined and, also it was determined the emissivity coefficient for the main determined values were:

- Convection coefficient α for steel 25.32 W/m^{2}K
- Convection coefficient α for copper 13.14 W/m^{2}K
- Emissivity coefficient ε [-] for steel was 0.07
- Emissivity coefficient ε [-] for copper was 0.03. [5]

The working value of the convection coefficient for aluminum is 29.5 W/m2K, emissivity coefficient for aluminum is 0.07 [-] and for brass is 13 W/m2K, and emissivity coefficient is 0.03 [-].[6]

Using a 3D experimental designed model in simulation represents a very important step in investigating a particular process. [7]

The most important process in this case will be based on the thermal simulation of the nozzle made from different materials to see thermal behaviour of the nozzle in different cases and to see which temperature is the best for the optimum material of the nozzle.

2.1 General consideration about the simulation study made

For simulation 1 of the temperature depending on the material of the nozzle, we used different metals for the parts under analysis, the heat transfer mode applied, the working temperature parameters and the convection coefficient as well as the emissivity coefficient, all according to the attached Table 1.

Table 1. Material for elements and thermal transfer

Number	Name of the element	Material	Thermal transfer
1	E3D Volcano nozzle	Steel	Convection
2	Cooling block	Aluminium	Convection Radiation
3	Thermal resistance	Steel	Radiation
4	Thermal separation tube	Steel	Convection Radiation
5	Heating block	Aluminium	Radiation

In the experimental study, the entire E3D Volcano assembly was used together with the related component parts of the assembly, they were created and assembled in the AUTODESK Inventor modelling program. This mode will help us prepare the studied assembly for thermal simulation using AUTODESK Fusion 360 Educational simulation software.

Note: The simulation process will be similar on the staged structure of the process from another past investigation study but on a different nozzle but still from the range of the E3D types, in which only the materials for the nozzle and other parts of the assembly will contribute to the final change.

The stages were similar with small changes to the materials of the nozzle as well as the values for convection and radiation coefficients:

1. Entering the assembly modelled in the Inventor program into the AUTODESK Fusion 360 simulation program [10].

2. Assignment of material for each individual piece of Study Materials:

- Nozzle - material made of:
  - Steel
  - Copper
  - Brass
  - Aluminum
- Hot block - aluminum 6061
- Threaded thermal tube - steel

- Cooling block - aluminum 6061
- Thermal resistance - steel
- Optional wire - ABS Plastic material

3. Applying the boundary conditions (Loads) for all analysed pieces:

- The heat applied to the thermistor was T=240 ^{o}C
- Convection application on the outer surface of the steel print head with the value of the convection coefficient 25.32 W/m^{2}C at the ambient temperature of 25 ^{o}C.
- Application of convection on the truncated surfaces of the steel separation tube with the value of the convection coefficient of 25.32 W/m^{2}C at the ambient temperature of 25 ^{o}C.
- Application of convection on the annular surfaces of the aluminum cooling block with the value of 29.5 W/m^{2}C of the convection coefficient at the ambient temperature of 25 ^{o}C.
- Application of radiation on the truncated surfaces of the separation tube with the value of the emissivity coefficient of 0.07 at the ambient temperature of 25 ^{o}C.
- Application of radiation on the frontal and truncated surface as well as on the back of the thermal resistance with the value of the emissivity coefficient of 0.07 at the ambient temperature of 25 ^{o}C.
- Application of radiation on the screw joint surfaces of the hot block with the value of the emissivity coefficient of 0.07 at the ambient temperature of 25 ^{o}C.
- Application of radiation on the annular surfaces of the cooling block with the value of the emissivity coefficient of 0.07 at the ambient temperature of 25 ^{o}C.

4. Application of contacts for all thermally charged surfaces.

5. Apply mesh with the value of 10% for data validation.

6. Data verification - Pre-check.

7. Simulation results

Note: For simulations 2, 3 and 4 we proceeded like the staged structure of simulation 1, with the modification of the material for the nozzle as well as the modification of the values for the convection and emissivity coefficients, all these data according to the general data Table 2.

2.2 Thermal study for nozzle made of steel material (OL) - Simulation

In the first simulation, steel material was used on the nozzle, thermal tube and thermal resistance, and aluminum material was used on the hot block and the cooling block, these being exposed to the ambient temperature T=25 ^{o}C and the temperature applied to the resistance was T =240 ^{o}C. Based on the convection coefficients for steel and aluminum as well as the emissivity coefficient for aluminum and steel, the temperature gradient was obtained according to the simulation Figure 2.

Table 2. Data table for materials used in the simulation

Number	Name of the element	Material type for E3D Volcano			
		Simulation 1	Simulation 2	Simulation 3	Simulation 4
1	E3D Volcano nozzle	Steel	Copper	Brass	Aluminium
2	Cooling block	Aluminium	Aluminium	Aluminium	Aluminium
3	Thermal resistance	Steel	Steel	Steel	Steel
4	Thermal separation tube	Steel	Steel	Steel	Steel
5	Heating block	Aluminium	Aluminium	Aluminium	Aluminium

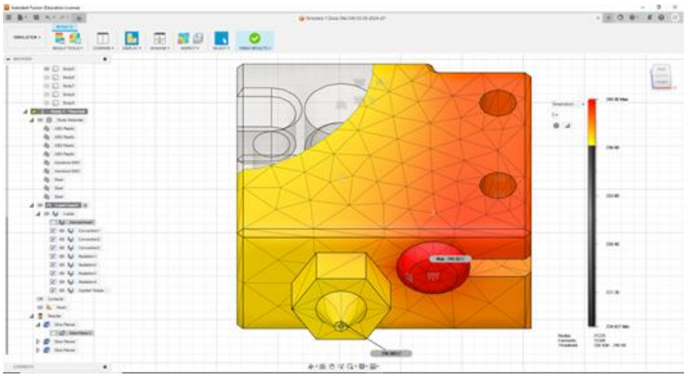

Figure 2. Temperature variation for the tip of the E3D VOLCANO nozzle made of steel material T=236.98 ^{o}C

The minimum temperature is 60.49 ^{o}C on the cooling block (dark blue area) and the highest heat concentration is on the right side of the hot block where the thermal resistance is located here the temperature reaches the threshold of 240 ^{o}C. In the steel material print head area, the temperature drops by about 5 ^{o}C reaching 236.99 ^{o}C in the nozzle hole area Figure 3.

For the E3D Volcano solution, the highest temperature is concentrated in the hot block on the side with the thermal resistance (the right side of the hot block) so that it dissipates from the right position of the resistance to the left direction of the nozzle without having large temperature drops Figure 4.

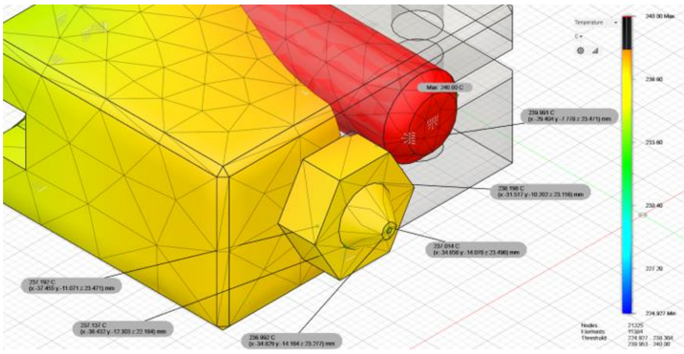

Figure 3. Temperature variation for the nozzle hole left side T=236.99 °C and right-side T=237.01 °C, tron conical area left-side T=237.13 °C and right-side T=238.19 °C and hexagonal area left T=237.19 °C and right-side T=239.99 °C

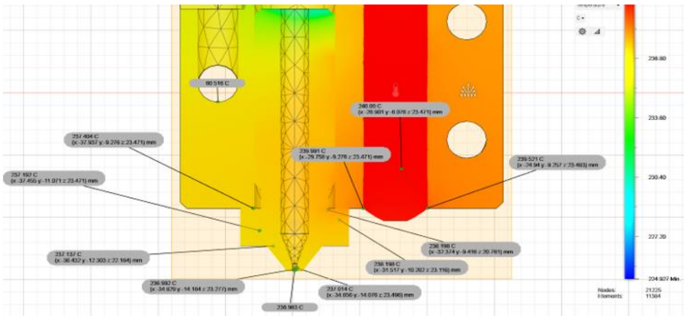

Figure 4. Temperature variation between the contact area with the hot block (left side T=239.99 °C and right-side T=239.52 °C), the thermistor area (T=60.51 °C) and the electrical resistance area (T=240 °C).

This decrease being a smooth one, thus signifying the fact that when the molten filament flows it will tend to make a U-shaped loop (hook) in the area of the nozzle hole on the right side with the resistor because the melting temperature differs on the right side (being all time longer on the side with the thermal resistance and slightly less on the opposite side) than the left side, so the flow will not be obstructed because the temperature does not have large drops on the hot block-resistor-nozzle assembly.

2.3 Thermal study for the nozzle made of copper material (Cu) - Simulation

In the second simulation, the temperature variation starts to change, as material was used plated copper for the analysed nozzle, so the temperature at the nozzle hole level increases to 238.13 °C, this temperature being higher by 1.15 °C compared to the steel material chosen before the nozzle in simulation 1 Figure 5.

Similarly, the temperature is higher in this case on the right side of the thermal resistance compared to the left side of the resistance and the temperature differences in this case do not exceed more than 2 °C compared to simulation 1 Figure 6 and Figure 7.

2.4 Thermal study for the brass material nozzle - Simulation

In simulation 3, the procedure was identical to the staged simulation mode according to simulation 1 and 2, here only the material of the E3D Volcano nozzle (brass material applied on the nozzle) was changed, as well as the values for the convection and radiation coefficients Figure 8.

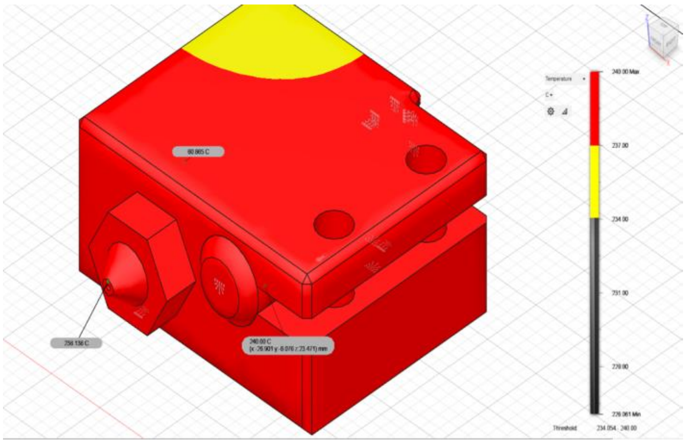

Figure 5. Simulation results 2 temperature variation for E3D VOLCANO nozzle made of copper material T=238.13 oC

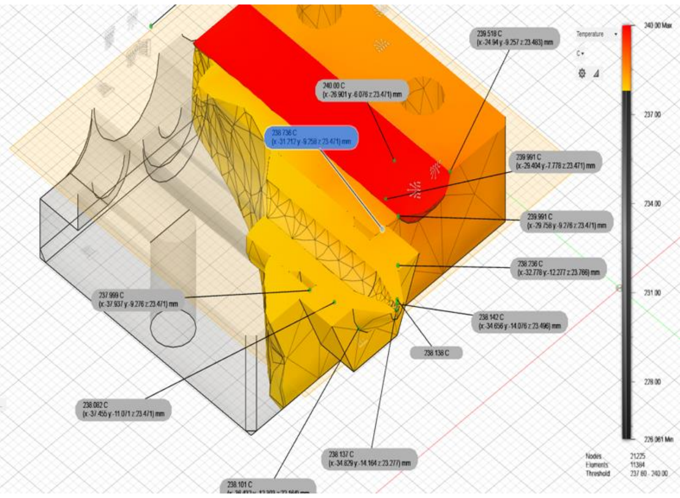

Figure 6. Temperature variation at the nozzle hole left side T=238.13 oC and right-side T=238.14 oC, left frustoconical area T=238.10 oC and right T=238.23 oC and left hexagonal area T=238.08 oC and right-side T=238.73 oC.

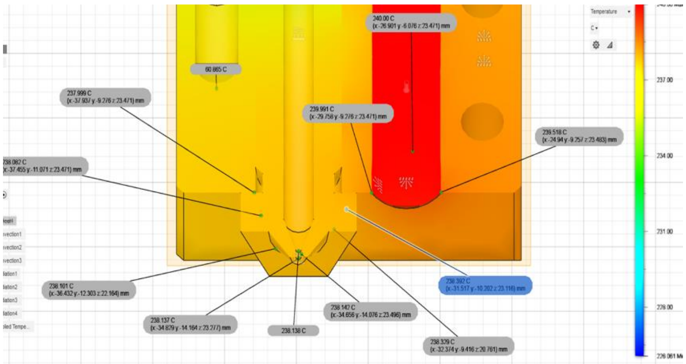

Figure 7. Temperature variation between the contact area with the hot block (left side T=239.99 oC and right-side T=239.51 oC), the thermistor area (T=60.86 oC) and the electrical resistance area (T=240 oC).

In simulation 3, the material used for the nozzle was brass, here the temperature at the nozzle hole was T=237.95^{o}C being almost similar with the temperature of the nozzle in simulation 2 where we had the value of 238.13 ^{o}C, the difference being by a few units (0.18^{o}C) Figure 8.

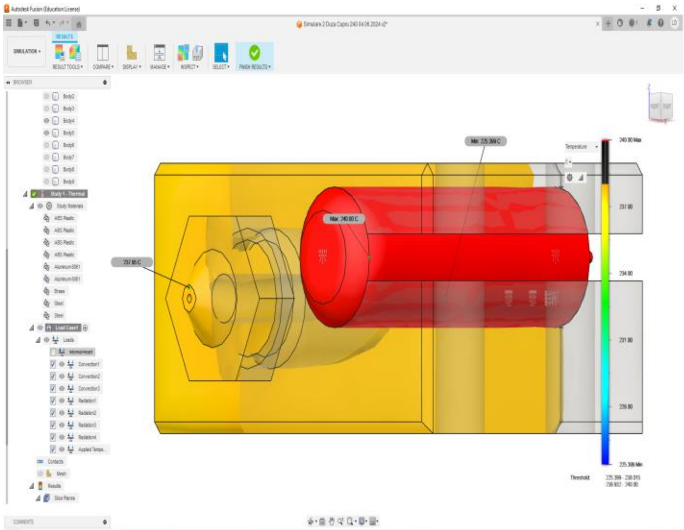

Figure 8. Simulation results 3 temperature variation for E3D VOLCANO nozzle made of brass material T=237.95 ^{o}C

It can be stated that both the copper nozzle from Figure 6 and Figure 7 and the brass nozzle from Figure 9 and Figure 10 are similar as extremely electrically and thermally conductive material, although they have different thermal conductivity values (copper thermal conductivity is 385 [W/(m*K)] and brass thermal conductivity is at value of 109 [W/(m*K)].

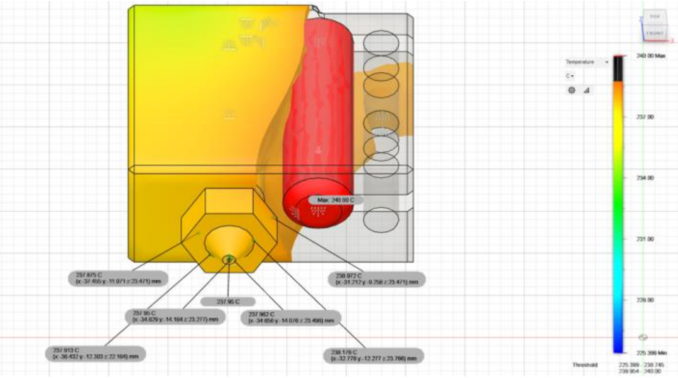

Figure 9. Temperature variation at the nozzle hole left side T=237.95 ^{o}C and right-side T=237.96 ^{o}C, left frustoconical area T=237.91 ^{o}C and right T=238.17 ^{o}C and left hexagonal area T=237.85 ^{o}C and right-side T=238.97 ^{o}C.

2.5 Thermal study for nozzle made of aluminum material (6061) - Simulation

In the last simulation the material used for the nozzle was aluminum 6061 and kept the same values of the convection and radiation coefficient, transfer modes and working temperatures Figure 11.

Following the Figure 12 we provided the temperatures at the tip of the nozzle made from aluminium material, and we specify the temperatures at the contact area with the hot block where the 2 screws should be inserted in. In this case the zone will also take over from the heat resulting in a dissipation.

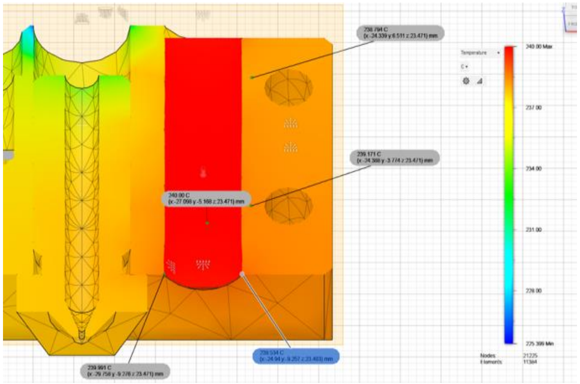

Figure 10. Temperature variation at the contact area with the hot block (left side T=239.99 ^{o}C and right-side T=239.54 ^{o}C), the thermistor area (T=60.67 ^{o}C), the electrical resistance area (T=240 ^{o}C) as well as bolt joint area (T=239.17 ^{o}C and T=238.79 ^{o}C)

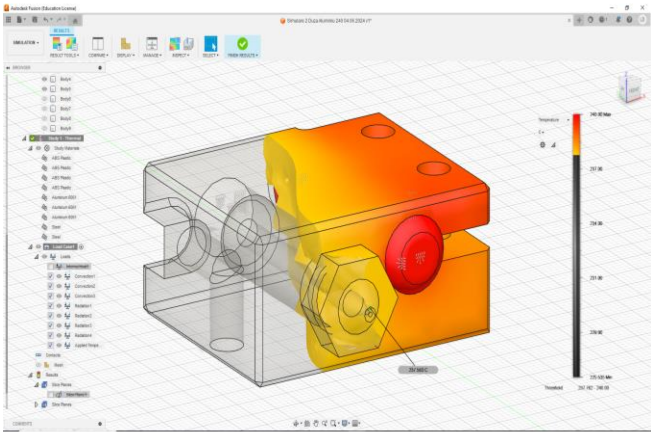

Figure 11. Temperature variation for the tip of the E3D VOLCANO nozzle made of aluminium material T=237.58 ^{o}C.

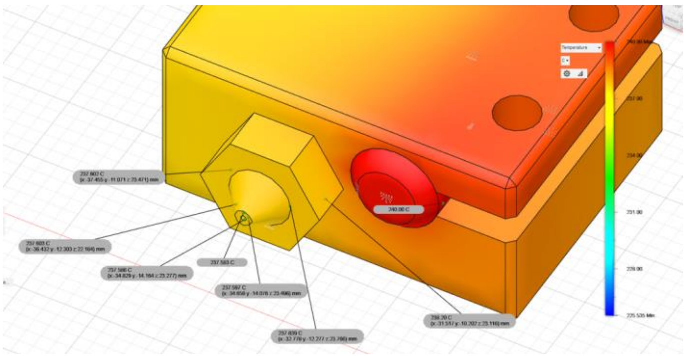

Figure 12. Temperature variation at the nozzle hole left side T=237.58 ^{o}C and right-side T=237.59 ^{o}C, left frustoconical area T=237.60 ^{o}C and right T=238.83 ^{o}C and left hexagonal area T=237.60 ^{o}C and right-side T=238.20 ^{o}C.

In the last simulation Figure 13 the material used for the nozzle was aluminium, here the temperature at the nozzle hole was T=237.58 ^{o}C being almost similar to the temperature of the nozzle in simulation 3 (brass) where we had the value of T=237.95 ^{o}C but also almost similar to the temperature of the nozzle from simulation 1 (steel) where we obtained the value of T=236.96 ^{o}C, the difference being from a few units to about 1 °C. It can be stated that both the copper nozzle, the brass nozzle and the steel nozzle are similar as extremely electrically or thermally conductive material, although they have different thermal conductivity values (copper thermal conductivity 385 [W/(m*K)], conductivity thermal conductivity of brass 109 [W/(m*K)] and thermal conductivity of steel 50.2 [W/(m*K)] [6].

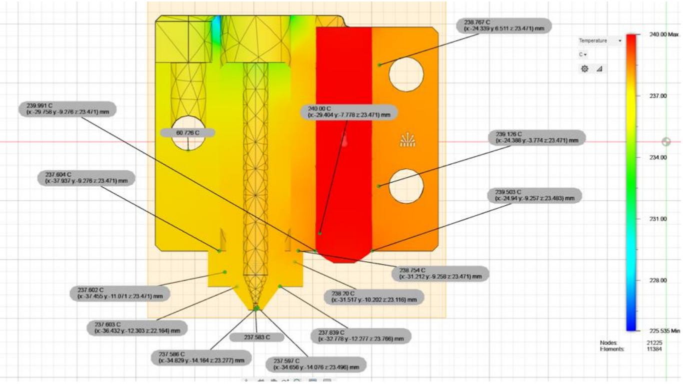

Figure 13. Temperature variation at the contact area with the hot block (left side T=239.99 °C and right-side T=239.50 °C), the thermistor area (T=60.72 °C), area with electrical resistance (T=240 °C), area of screw joint (T=239.12 °C and T=238.76 °C) as well as the contact area of the nozzle with the hot block (left side T=237.60 °C and right-side T=238.75 °C)

3. EXPERIMENTAL ANALYSIS OF THE RESULTS OBTAINED BASED ON THE THERMAL SIMULATION

The experimental data analysis was made with the purpose to indicate the differences of the temperature that occur on the E3D Volcano nozzle made from different materials, for all 4 simulations. This will provide necessary data to correctly choose the material for the future experiments.

In the data analysis we provided based on each simulation, a table with different values of each simulation material.[11, 13]

3.1 Graphical analysis of the temperature based on each material at the front position of the 0,4 mm orifice nozzle.

For the first analysis the largest temperature difference is on the steel nozzle which has a 2% temperature difference and for all other material are 1% which can be seen in Table 3.

Table 3. Difference of the temperature based on each material at the front position of the 0,4 mm orifice nozzle.

Simulation	Material nozzle	Temperature on the nozzle orifice [°C]		ΔT [°C]
		left side	right-side	
1	Steel	236,99	237,01	0,02
2	Copper	238,13	238,14	0,01
3	Brass	237,95	237,96	0,01
4	Aluminium	237,58	237,59	0,01

ΔT – represents the temperature difference between a high point and a lower point of each individual material used on the E3D Volcano Nozzle.

It can be stated that in the first data analysis, the higher value of the temperature was on the steel nozzle, here the differences were of the highest compared to the rest of the materials T=237.01 °C - 236.99 °C =0.02 °C which resulted in a 2% difference of temperature for the ΔT provided in Figure 14.

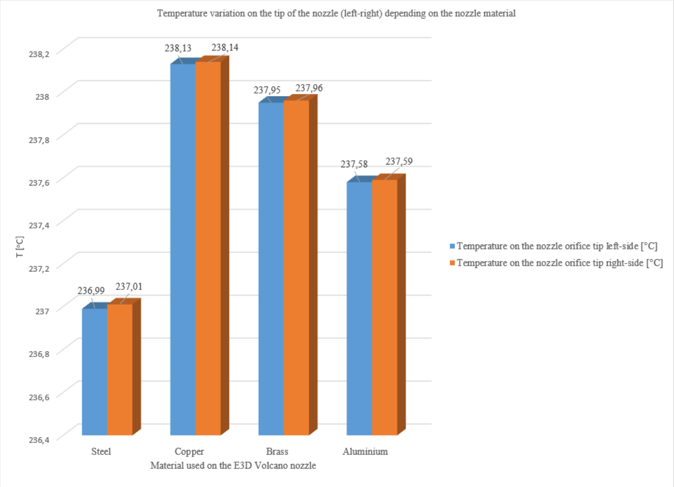

Figure 14. Histogram of the temperature based on each material at the front position of the 0,4 mm orifice nozzle

3.2 Graphical analysis of temperature at the large diameter base of the frustoconical area of nozzle.

For the secondary analysis the biggest temperature difference is on the aluminum nozzle, based on the Table 4 calculus we represented the difference as T=238.83 °C - 237.6 °C =1.23 °C at the tip of the aluminium nozzle shown in Figure 15.

From the analysis of the centralized data in Table 4, the largest temperature difference is for the nozzle made of brass, followed by the one made of copper with a difference of half the difference of the one obtained for brass and a small difference of that of copper for aluminium. The smallest difference is obtained for the steel nozzle.

Table 4. Difference of the temperature based on each material at the large diameter base of the frustoconical area of nozzle.

Simulation	Material nozzle	Temperature on the nozzle orifice [°C]		ΔT [°C]
		left side	right-side	
1	Steel	237,13	238,19	1,06
2	Copper	238,1	238,23	1,39
3	Brass	237,91	238,17	2,69
4	Aluminium	237,6	238,83	1,23

ΔT – represents the temperature difference between a high point and a lower point of each individual material used on the E3D Volcano Nozzle.

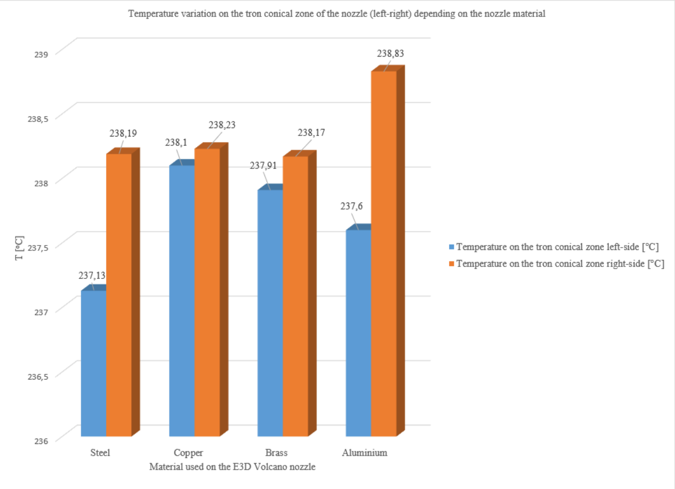

Figure 15. Histogram of the temperature based on each material at the large diameter base of the frustoconical area of nozzle

3.3 Graphical analysis of temperature at the front top of hexagonal area of nozzle.

For the secondary analysis the biggest temperature difference is on the aluminum nozzle, based on the Table 4 calculus we represented the difference as T=238.83 °C - 237.6 °C =1.23 °C at the tip of the aluminium nozzle shown in Figure 15.

From the analysis of the centralized data in Table 5, the largest temperature difference is for the nozzle made of brass, followed by the one made of copper with a difference of half the difference of the one obtained for brass and a small difference of that of copper for aluminium. The smallest difference is obtained for the steel nozzle.

Table 5. Difference of the temperature based on each material at the large diameter base of the frustoconical area of nozzle.

Simulation	Material nozzle	Temperature on the nozzle orifice [°C]		ΔT [°C]
		left side	right-side	
1	Steel	237,13	238,19	1,06
2	Copper	238,1	238,23	1,39
3	Brass	237,91	238,17	2,69
4	Aluminium	237,6	238,83	1,23

ΔT – represents the temperature difference between a high point and a lower point of each individual material used on the E3D Volcano Nozzle.

3.4 Graphical analysis of temperature at the small diameter external cylindrical area of heat break element.

On the last analysis the biggest temperature difference is on the aluminum nozzle, here the difference was T=239.99 °C – 239.5 =0.49 °C where the ΔT shown in Table 6.

From the analysis of the centralized data in Table 6, the largest temperature difference is for the aluminium nozzle, followed by the one made of steel and approx. equal difference for copper and brass material of the nozzle was the smaller difference.

Table 6. Difference of the temperature at the small diameter external cylindrical area of heat break element.

Simulation	Material nozzle	Temperature on the nozzle orifice [°C]		ΔT [°C]
		left side	right-side	
1	Steel	239,99	239,52	0,47
2	Copper	239,99	239,51	0,48
3	Brass	239,99	239,54	0,45
4	Aluminium	239,99	239,5	0,49

ΔT – represents the temperature difference between a high point and a lower point of each individual material used on the E3D Volcano Nozzle.

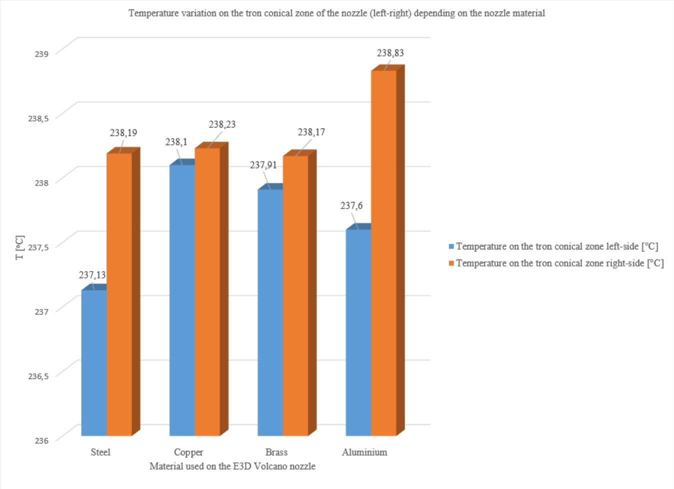

Figure 16. Histogram of the temperature at the small diameter external cylindrical area of heat break element

4. CONCLUSIONS

In all 4 simulations, a wire composed of 4 segments made of ABS material, with a diameter of 2 mm, was used, being inserted inside the assembly. The transposition of the wire within the 4 thermal simulations had the role of observing the thermal behaviour that takes place both at the level of the assembly and at the level of temperature change on the entire assembly.

Similarly for all 4 simulations I represented the E3D Volcano assembly composed of nozzle, hot block, cooling block, resistor, threaded thermal tube and simulated wire before the occurrence of the shock and after the occurrence of the thermal shock.

All 4 materials assigned to the nozzle are optimal, they do not exceed the value of 240 oC, which will contribute both to the flow part of the molten filament and to the part of temperature change in case of thermal shock.

For the 4 simulation levels where steel, copper, brass, and aluminum materials were used, the thermal behaviour for different simulation conditions highlights the fact that all these materials exhibit an extremely efficient thermal conductivity. The variation of temperatures between the 4 types of materials chosen, with differences of 1 °C to 4 °C around the flow hole, indicates that all these materials have thermal capacity to distribute and maintain heat in a relatively uniform manner. At the same time, the temperature in the thermistor area remained almost constant at T=60 ^{o}C, and the temperature gradient for all 4 simulations usually appears in the threaded tube where the temperatures are concentrated from maximum to minimum, with the recommendation that the threaded thermal tube be wrapped in a Teflon tape to better isolate this area extremely subject to temperature variation.

From the data analysis ΔT which represent the temperature difference (expressed in %) it has minimal differences of temperature referring to the range of T=0.02 ^{o}C to a maximum of T=2.8 ^{o}C.

Finally, based on the 4 simulations we can state that steel, copper, brass, and aluminum material are materials that have close thermal performance under different loading conditions, each material has its specific advantages according to requirements and applications and this highlights the importance choosing the right materials according to the specific requirements of each product, considering both the importance of the material properties and the operating conditions.

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