Nonconventional Technologies Review
Romania, Iunie, 2024

CONSTRUCTIVE AND TECHNOLOGICAL CONSIDERATIONS ON THE FLOW OF THERMOPLASTIC MATERIAL THROUGH THE E3D VOLCANO PRINTING NOZZLE DEPENDING ON THE DIAMETER OF ITS HOLE

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ABSTRACT: The paper deals with thermal analysis and the mode of heat dissipation on the surfaces of the 3D printer parts. The paper presents both the 3D modelling part of the components related to the E3D Volcano assembly, the realization of the simulation models using the necessary conditions for the heat transfer phenomenon, more precisely in the current study we will only use thermal convection and thermal radiation as well as the realization of a mathematical calculation regarding the thermal part using real values. Very important in this case are also the materials used for each part of the assembly because they play an important role in heat transfer regarding thermal conductivity. Also, in the final part of the paper, the simulation after the mathematical power calculation is proposed regarding the evolution of the temperature on the entire E3D Volcano assembly and the graphic representation of the diagram T [ºC] according to the power of the resistance P [W].

KEYWORDS: additive manufacturing, heat transfer, materials, simulation ,3d modelling, thermodynamic calculation

1. INTRODUCTION

Optimizing production capacity is one of the most substantial goals of every manufacturing industry. They intend to achieve mass customization without sacrificing efficiency or the benefits of economy of scale in terms of ROI. As a result, the ability to respond to customer requirements in a fast and flexible manner, while retaining many versions at small batch sizes, needs to increase. The implementation of a customizable, programmable, and fully integrated large-scale production system is useful precisely to address this problem to software, hardware, and material. This concept represents a great advance in the design industry, thanks to the time-saving factor and subsequent cost-effectiveness component. This design method also challenges sustainability goals. It improves material reduction in the manufacturing process and the subsequent effect of generating less waste at the end of product life. [1].

3D printing offers many potential benefits in construction, such as the ability to produce efficient structural shapes for individual components, exploit the full potential of a material, reduce waste, and make significant savings in time and overhead costs. A possible integration between Building Information Modelling (BIM) and 3D printing would be extremely beneficial in reducing the overall time required for construction projects. 3D printing of cement materials, fibre-reinforced concrete, and reinforced concrete, has been reported to offer new technological challenges; Significant research is ongoing in this area [2].

The terminology "volcano hot end" refers to a specific type of hot end, namely the specific construction and geometry of a nozzle used in printing. In the context of additive manufacturing, the hot end is the component responsible for heating and melting the filament (wire or granular material), allowing it to be extruded layer by layer to create a 3D printed object. The Volcano hot end is a product developed by the company E3D; a company known for producing high-quality 3D printing components. The Volcano hot end is designed with a heating block and a specific nozzle, which are much longer than the simple V6 variant, and allow faster and more substantial extrusion of the filament or granular material. This design is ergonomic when increasing print speed or depositing more material in each layer, which might be beneficial for certain applications, such as large prototypes or parts that require much greater strength [3]. The extended length of the Volcano hot end helps maintain a constant temperature throughout the longer melting zone, allowing for higher filament flow without compromising print quality. It is worth noting that using a warm Volcano end may require adjustments to print settings, such as temperature, layer height, and layer thickness, to achieve optimal results. The process produces parts by extruding a material, usually a thermoplastic polymer. The thermoplastic material is pushes through a nozzle, which translate in the X, or Y direction to create a two-dimensional layer. This layer represents a section of the digital model of the solid to be manufactured. To ensure proper fusion between layers of material, the base on which the first layer or machine enclosure is deposited is heated. Where needed, support material can be deposited using a separate nozzle and removed by different methods after completion of manufacture. The precision and accuracy of the process is determined by the dimension of the nozzle, which can have diameters of the order of tenths of a millimetre [4] Figure 1.

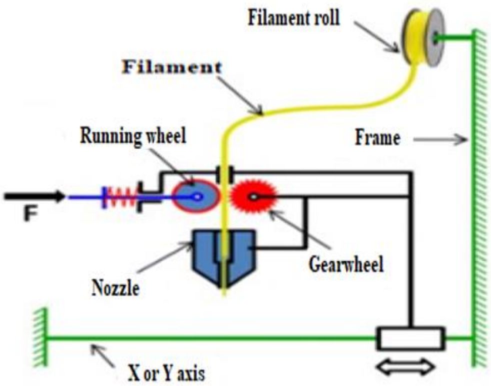


Figure 1. Diagram of the principle of additive manufacturing by molten filament deposition

2. CONSTRUCTIVE AND TECHNOLOGICAL CONSIDERATION OF THE EXTRUDER USED IN THE THERMAL SIMULATION.

2.1 Constructive considerations on the realization of the extruder assembly

The components of the E3D Volcano assembly are identical with the other elements from the E3D V6 Solution with the change in dimensions and geometry of the hot block, print head and thermal resistance. The rest of the elements are like the E3D Solution [5].

2.2 Technological considerations the parts of the assembly

Manufacturing technology is a set of processes, operations or technical conditions that are carried out to achieve a certain part, machine organ or other constructions of industrial nature, etc.

In automotive manufacturing technology we can meet several types of processing performed with the help of several processing machines controlled by an operator or automated (CNC type) being listed in Table 1 regarding the stages of realization by manufacturing technology of the components in the analysed assembly as well as the materials used Figure 2.

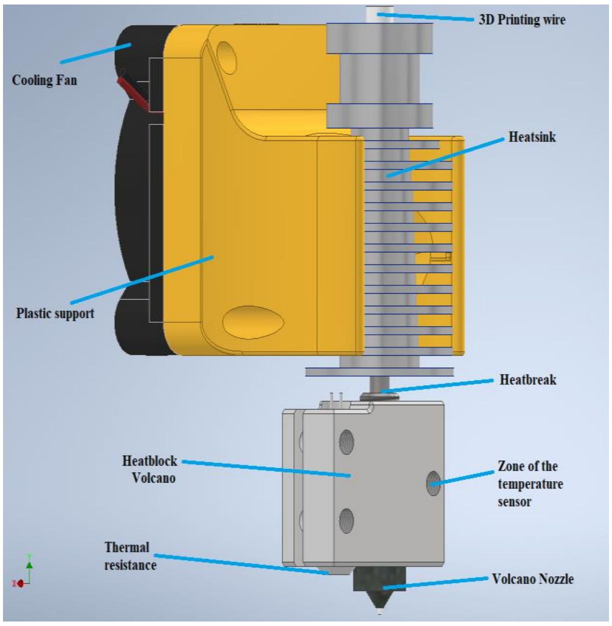


Figure 2. E3D Volcano assembly design

The main mode of manufacturing the parts that make up the E3D Volcano assembly are similar according to the E3D V6 solution, here being different only the material assigned to the warm block, the print head and thermal resistance, the rest of the parts being like E3D V6 [5].

3. LIST EXAMPLES (HEADING 1)

In the experimental study, the entire E3D Volcano assembly was used together with the related component parts, they were created in the AUTODESK Inventor modelling program and the assembly was done in the same program.

This mode will help us prepare the studied assembly for thermal simulation using the AUTODESK Fusion 360 Educational simulation software.

Table 1. Manufacturing process and materials used in the construction of parts in the assembly.

Number	Name of the element	Materials	Manufacturing process
1	Heating Block	Steel, Aluminium	CNC lathe, milling machines
2	Printing nozzle	Brass, Copper, Steel	Cutting tools, drilling tools
3	Thermal resistance	Steel	Lathe, CNC
4	Thermal separation tube	Steel	Lathe, drilling machines
5	Cooling block	Aluminium, Steel	Cutting tools, casting, milling machines, drills
6	Heatsink cooling bracket	Plastic	Molds, material injection, 3D printing
7	Cooling fan	Plastic	Molds, material injection, 3D printing

The interest was to simulate two hypotheses for the temperature part of the material PLA $T = 210\ ^{o}C$ and for the ABS material $T = 240\ ^{o}C$, using a thermal resistance of 50 W.

3.1 Simulation 1 ABS T=240 ^{o}C Below is an example of a bulleted list:

Inserting the created assembly with the help of AUTODESK Inventor program into the

AUTODESK Fusion 360 simulation program from the program menu a DESIGN button was selected and then we chose SIMULATION, then selecting the Thermal window Figure 3.

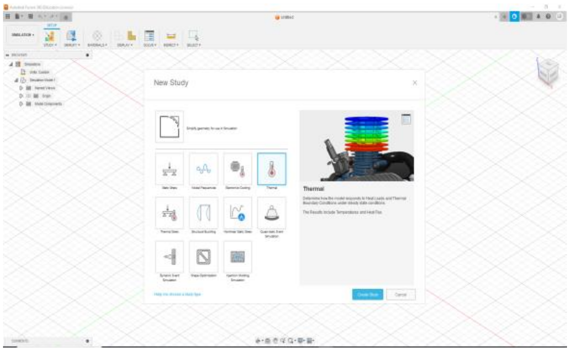
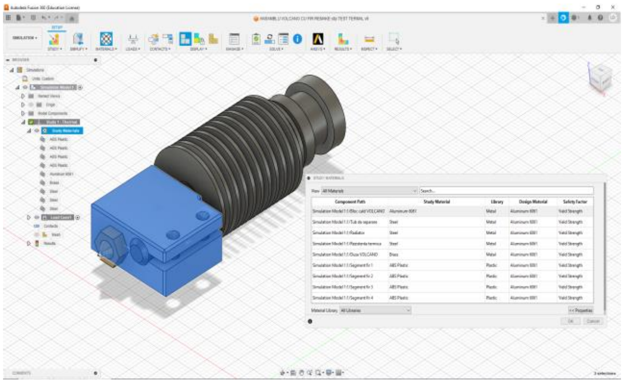


Figure 3. Thermal simulation

The assignment of material for the component parts of the entire assembly is done from the program tree by selecting Study Materials where, according to the table in the program, we entered the materials used for each part Figure 4, as follows:

- The nozzle/print head has been assigned brass-based material (brass);
- The hot block received as material aluminium 6061;
- The threaded thermal tube received steel as a material;
- The cooling block (thermal radiator) received steel as a material;
- The thermal resistance received steel as a material;
- The wire inserted into the assembly received as ABS Plastic material;



Component Path	Study Material	Library	Design Material	Safety Factor
Simulation Model 1:1/Bloc cald VOLCANO	Aluminum 6061	Metal	Aluminum 6061	Yield Strength
Simulation Model 1:1/Tub de separare	Steel	Metal	Aluminum 6061	Yield Strength
Simulation Model 1:1/Radiator	Steel	Metal	Aluminum 6061	Yield Strength
Simulation Model 1:1/Rezistenta termica	Steel	Metal	Aluminum 6061	Yield Strength
Simulation Model 1:1/Duza VOLCANO	Brass	Metal	Aluminum 6061	Yield Strength
Simulation Model 1:1/Segment fir 1	ABS Plastic	Plastic	Aluminum 6061	Yield Strength
Simulation Model 1:1/Segment fir 2	ABS Plastic	Plastic	Aluminum 6061	Yield Strength
Simulation Model 1:1/Segment fir 3	ABS Plastic	Plastic	Aluminum 6061	Yield Strength
Simulation Model 1:1/Segment fir 4	ABS Plastic	Plastic	Aluminum 6061	Yield Strength

Figure 4. Assigning materials to each part individually

Application of the boundary conditions from the load's menu for all studied parts, here the following input data was used in the form of a phased structure: Internal heat was at 50 W, on the thermal resistance, by selecting the whole body (1 body in the selected parts) Figure 5.

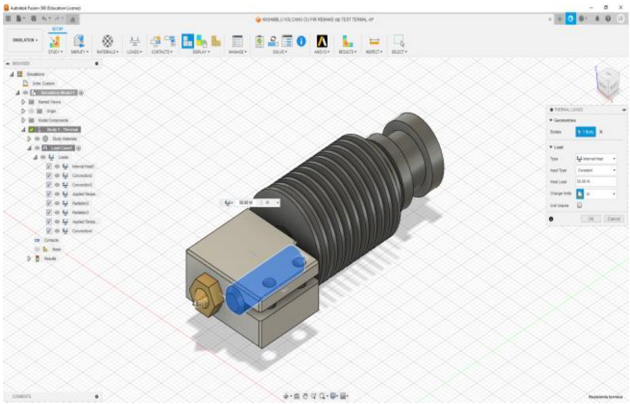


Figure 5. Applying internal heat on the thermal resistance with the value of 50 W

The importance of the heat phenomenon, in terms of theoretical aspects related to heat exchange, has the following modes of heat transfer:

- Thermal conduction;
- Thermal convection;
- Thermal radiation;

The necessary condition for heat transfer (Q) is related to the existence of a temperature difference. For the current study we will use only thermal convection and thermal radiation.

Thermal convection is a mode of heat transfer (Q) that occurs between a moving fluid and a surface in contact with that fluid. If the movement of fluid occurs due to the pressure difference (whether it is a pump or blower) we will face the phenomenon of forced convection [6]. In another case, if fluid movement occurs due to the difference in density (if we have temperature) we will have free convection [7]. Application of convection only to the outer surface of the print head (tapered part and faces of hexagon) with a value of 13 W/m^{2}C (values for copper, brass, other alloys) at ambient temperature of 25 ^{o}C Figure 6.

Application of convection to the externally exposed surfaces of the threaded steel separation tube with a value of 25.32 W/m^{2}C (values for steels) at ambient temperature of 25 ^{o}C Figure 7.

Application of convection to the ring surfaces of steel cooling block with a value of 25.32 W/m^{2}C (values for steels) at ambient temperature of 25 ^{o}C Figure 8.

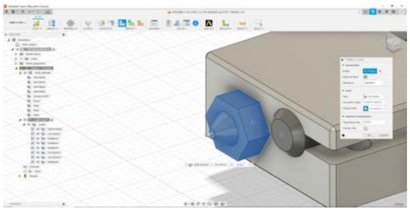


Figure 6. Applying convection on the exterior surface of the brass nozzle

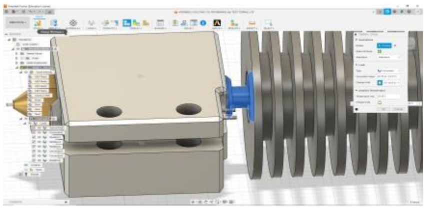


Figure 7. Applying convection on the surfaces of the separation tube

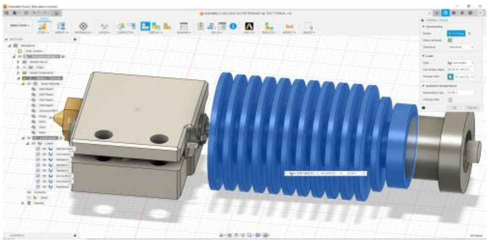


Figure 8. Applying convection on the ring surfaces of the cooling block

Thermal radiation is a double mode of heat transfer (Q), where in the first phase thermal heat turns into electromagnetic waves and when the waves reach the surface of another body it turns into heat [6]. Electromagnetic radiation for any type of body is due to the conversion of its internal energy into electromagnetic energy, it is called thermal radiation.

If the body is not near an energy source to replenish its internal energy, then that body will radiate all its available energy, so the temperature will be closer to absolute zero. Application of radiation to the externally exposed surfaces of a threaded steel separation tube with an emissivity coefficient value of 0.07 at ambient temperature of 25 ^{o}C Figure 9.

Application of radiation to the surface behind the resistance (the area of input of the two wires) but also to the surfaces exposed to the outside of the steel thermal resistance with the value of the emissivity coefficient of 0.07 at ambient temperature of 25 ^{o}C Figure 10.

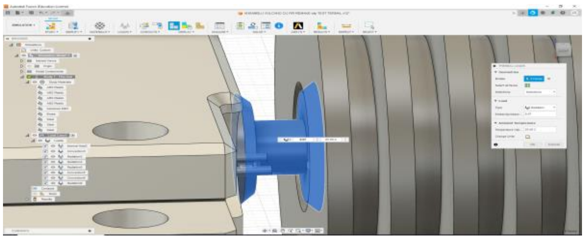


Figure 9. Applying radiation on the conic surfaces of the separation tube.

Application of radiation to the screw joint surfaces of the aluminium heating block with the emissivity coefficient value of 0.07 at ambient temperature of 25 ^{o}C Figure 11.

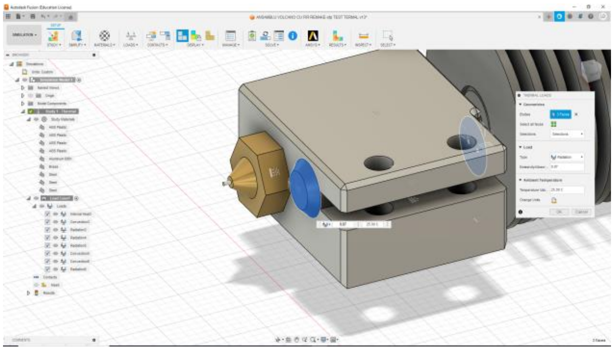


Figure 10. Applying radiation on the front surface and the back surface of the thermal resistance

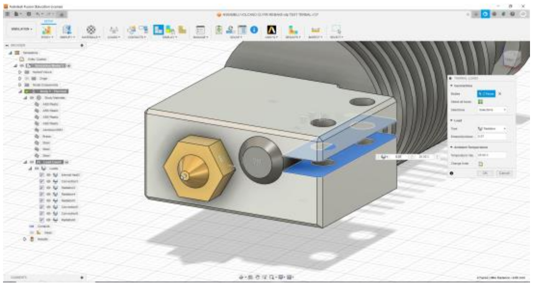


Figure 11. Applying radiation on the screw joint surfaces of the aluminium heating block

Application of radiation to annular surfaces of steel cooling block with emissivity coefficient value of 0.07 at ambient temperature of 25 ^{o}C Figure 12.

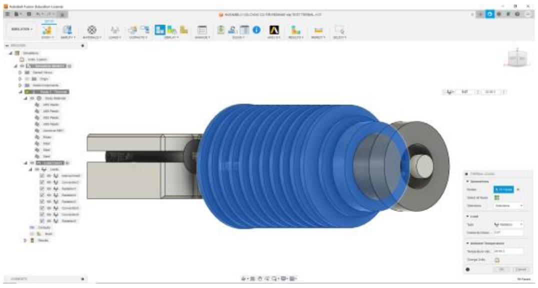


Figure 12. Applying radiation on the ring surfaces of the cooling block

The application of contacts between all thermally charged surfaces in symmetrical mode so no errors will occur at the time of thermal simulation Figure 13.

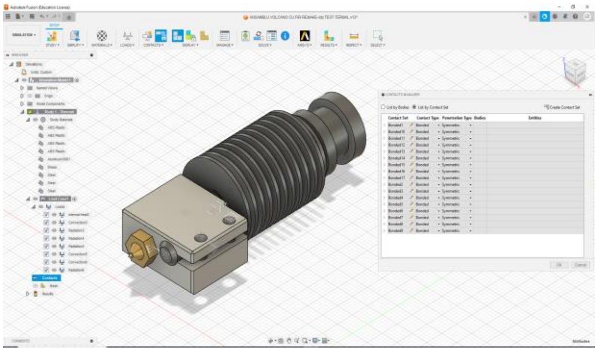


Figure 13. Applying contacts between all thermally charged surfaces.

Use of 10 % mesh for the whole assembly for data validation, and use of thermal study type to simulate temperatures.

After applying all loads, materials, contacts and mesh, a check will be used from the program menu by selecting the Pre-check window and it must be green so that there is no data that is not valid and there are no errors for the simulation, after which you will press the Simulate button to start the simulation itself Figure 15.

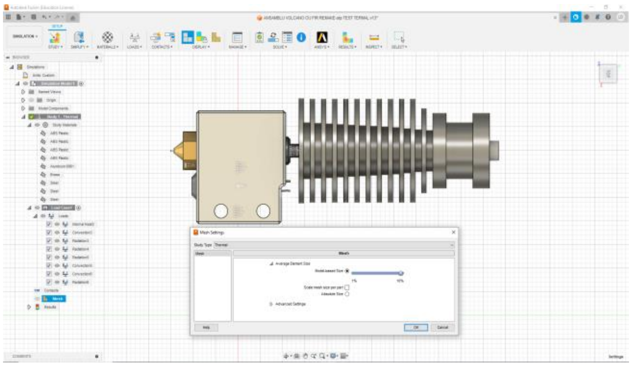


Figure 14. Using Mesh at 10%.

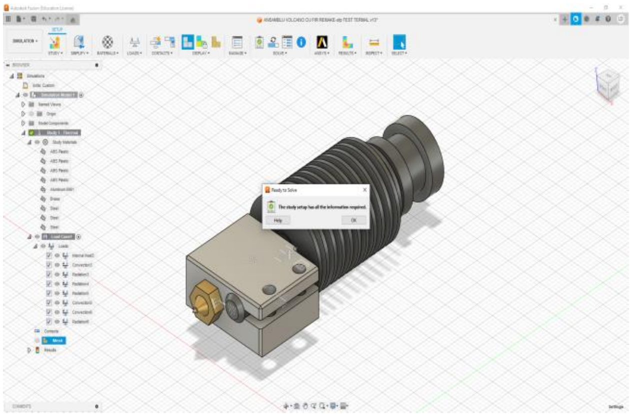


Figure 15. Data validation (Pre-check).

The main simulation can take a shorter or longer period depending on the chosen degree of load. The AUTODESK Fusion 360 simulation software will simulate with precision calculation with 100 iterations to obtain the temperature gradient. At the same time, the period of determination (time) of evolution of heat transfer from the hot source to the components is a slow process, which is why sampling of the simulation with a frequency of less than a few hundred or thousands of seconds is not recommended. After the simulation time is over, we will obtain the temperature diagram for ABS T=240 °C, so in this case we dropped the watt parameter of the 50 W resistance and replaced it with the temperature applied to the resistance with the value of 240 °C.

3.2 Simulation 2 PLA T=210 °C

Similar was done in the case of simulation 2, only in this case the temperature applied to the thermal resistance was 210 °C and thus respecting the other common data to obtain the temperature diagram Figure 17 [9, 10].

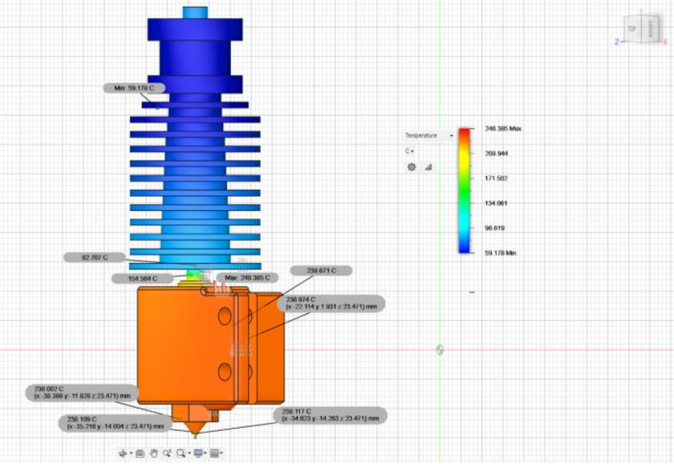


Figure 16. Simulation results – Temperature diagram for ABS T=240 °C.

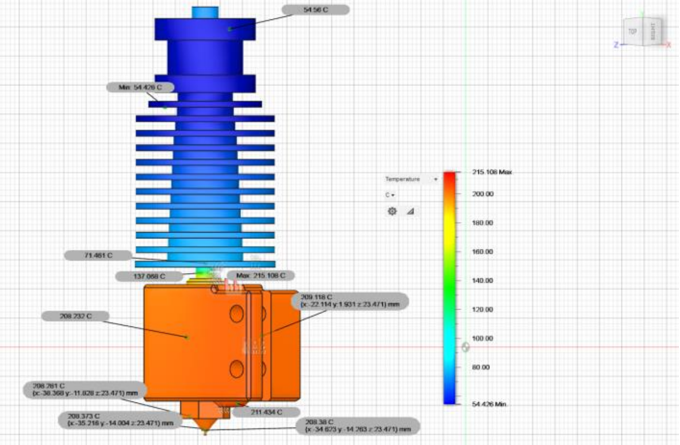


Figure 17. Simulation results – Temperature diagram for PLA T=210 °C.

The thermal influence on the assembly consists in the power calculation of the thermal resistance, which is why in the real simulation after thermodynamic calculation. In the calculation part, we abandoned the application of the internal temperature of 210 °C and 240 °C on the surface of the resistance and replaced with power values from 1 to 50 W. For this calculation it was necessary to use Stefan-Boltzmann's law equation 1:

$$P=\sigma*A*T^{\wedge 4} \tag{1}$$

where:

- P – power =50 [W];
- σ represents the constant Stefan-Boltzmann = 5,6*10^{-8} [$Wm^{-2}K^{-4}$];
- A represents the area of the resistance surface [m^2];
- T – surface temperature [K];

The main value for the surface area was calculate using equation 2:

$$A=2*\pi*r*h \tag{2}$$

where:

- r represents the radius = 3 [mm];

- h represents the height of the cylinder surface = 20 [mm];

The result of the surface area is A=376,991 [mm^2]

To determine the emitted temperature of the 50-watt resistor we rearranged the equation 3 as:

$$T= \llbracket (P/(\sigma*A)) \rrbracket ^{(1/4)}=1236,69\ [K] \qquad (3)$$

After finding out the temperature value, we can proceed to the final calculation of the resistance power equation 4.

$$P=\sigma*A*T^{\wedge 4}=50\ [W] \qquad (4)$$

Transformation from Kelvin to Celsius of the calculated temperature: 1236,69 °K -273.15 °K = 963,54 °C [8].

The simulation after the calculation ran using internal heat on the thermal resistance with the value of 50 W, so we obtained the temperature diagram that actually attests to the reality of the calculation made previously, where our maximum temperature reaches the threshold of about 909 °C, the difference in temperature calculation being 54.54 °C due to the fact that in the simulation in addition to the temperature level on the surface of the resistance diminishes due to convection phenomena (displacement in the gaseous medium of assembly according to XY directions after machining) and radiation (due to external radiant surfaces of assembly components). This leads us to assert that the value obtained by simulation is closer to the true value than the temperature value determined by mathematical calculation Figure 18.

After the simulation with the 50 W resistance, a series of calculations followed for resistance values of 40 W, 30 W, 20 W, 10 W and 1 W to represent the temperature diagram T [oC] depending on the power of resistance P [W], thus obtaining the following Table 2 values Figure 19.

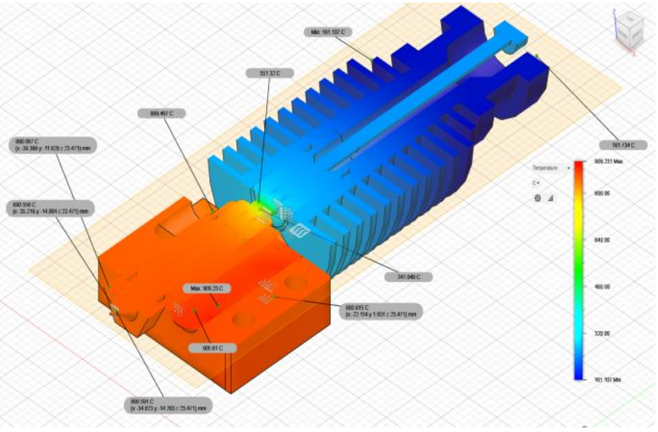


Figure 18. Simulation results – Temperature diagram after actual calculation using a thermal resistance with a power of P=50 Watts.

4. CONCLUSIONS

For simulation 1 ABS T=240 °C [11] it can be observed how the temperature reaches a maximum of 246 °C in the thermal resistance zone, according to the assigned loads (convection on the nozzle surfaces, on the troncon area of the separation tube and on the annular surfaces of the cooling block; radiation for the joining surfaces of the warm block, annular surfaces of the cooling block, troncon surfaces of the separation tube, front surface and bottom of thermal resistance) and the minimum temperature reaches 56 °C somewhere on the annular surface of the outside of the cooling block. The most thermally exploited area is in the middle of the threaded separation tube, where temperatures reach values from 90 °C to 220 °C.

Table 2. The series of calculations followed for resistance

Power [W]	Temperature [oC]	Obs.
50	963,55	
40	896,45	
30	815,28	
20	710,36	
10	553,88	
1	191,92	

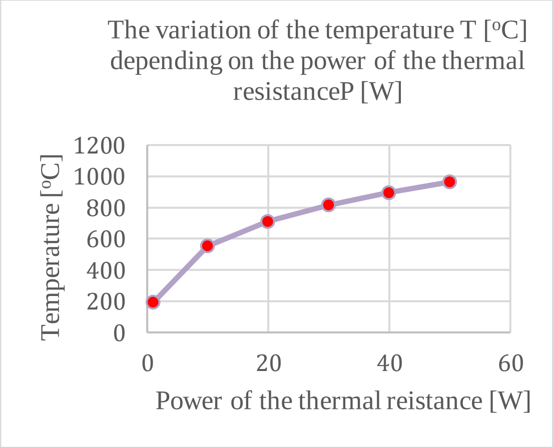


Figure 19. Variation of the temperature T [°C] depending on the power P [W].

For simulation 2 PLA=210 °C the maximum temperature reaches the threshold of 215 °C in the thermal resistance zone and the minimum is 54 °C on the annular zone of the cooling block.

The thermal behaviour of the two simulations is identical except for a temperature difference applied separately to the resistance surface, the difference being 20 °C.

The thermal behaviour of the assembly, using a thermal resistance with a power of 50 W, here may differ from a thermodynamic point of view because in the first 2 simulations we gave up the power parameter P [W] and in the last phase we reintroduced this parameter and gave up the heat applied to the resistance, thus keeping the other input data, so we can conclude that the power with which the thermal resistance is supplied is not 50 W (for the first 2 simulations) but is a power controlled by the module that checks the temperature level between two limits, which is why it is called closed-loop mode, maintaining a voltage time and a break time dependent on the temperature measured with the thermocouple arranged on the warm block.

At the position level, where the thermocouple is mounted, the temperature determined by simulation in the 2 variants was 207 ^{o}C (with a temperature difference of 3 ^{o}C) for the simulation with a temperature of 210 ^{o}C on the outer surface of the resistance and 236 ^{o}C (having a difference of 4 ^{o}C) for the simulation with a temperature of 240 ^{o}C on the outer surface of the resistance.

The thermal behaviour is the same for both variants with resistance and temperature on the surface, presenting only the variant with power P [W].

The variation of temperature depending on the strength of the resistance indicates that both quantities are directly proportional, the temperature decreases the moment we decrease the strength of the resistance.

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