



Research Paper

## A Computational Method for the Design of the Heating Zone in FDM 3D Printer Extruders Paper Title

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**ABSTRACT:** This study introduces a computational method to analyze the thermal distribution and heat transfer behavior in the heating zone of Fused Deposition Modeling (FDM) 3D printer extruders. The model evaluates key parameters such as filament throughput, volumetric flow rate and required thermal energy based on process variables including nozzle diameter (0.2–0.8 mm), layer thickness (0.1–0.3 mm) and printing speed (50–150 mm/s). Numerical simulations conducted using CAD Simulation revealed that at 0.3 mm layer thickness and 150 mm/s speed, the filament feed rate reached 18 mm<sup>3</sup>/s, leading to a considerable increase in thermal loading. When a 0.8 mm nozzle was used central regions showed elevated temperatures whereas peripheral areas exhibited non-uniform thermal gradients. Higher printing speeds caused insufficient heating zones to expand potentially weakening interlayer adhesion. The results highlight that heating zone design in FDM systems should move beyond static temperature assumptions and instead incorporate parametric process modeling and computational thermal optimization. The proposed approach enables tailored engineering driven extruder designs that improve thermal efficiency and part quality supporting design for additive manufacturing (DfAM) strategies.

**KEYWORDS:** FDM, Extruder Heating Zone, Thermal Simulation, Filament Feed Rate, Parametric Design Optimization

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### I. INTRODUCTION

In recent years, there has been a significant increase in interest toward Additive Manufacturing (AM) technologies, primarily due to their ability to serve a broad range of users, enable rapid prototyping and enhance design flexibility. AM methods are widely utilized in various sectors including aerospace, automotive, medical, biomaterials, tooling, and education owing to their effectiveness in fabricating complex geometries that are often challenging to produce through conventional manufacturing techniques [1].

Among these technologies, Fused Deposition Modeling (FDM) stands out due to its cost-effectiveness, user-friendly nature and broad material compatibility. FDM is based on the layer by layer deposition of thermoplastic materials in their molten state. Commonly used filaments include engineering grade polymers such as ABS, PLA, PETG and TPU each possessing distinct thermal and rheological properties that directly influence print quality [2].

Every FDM 3D printer is configured according to its intended application, print resolution and compatible materials. The mechanical and thermal performance of the system depends on multiple process parameters, including print speed, layer height, nozzle diameter, extruder architecture and thermal control mechanisms. Notably, the extruder unit, often referred to as the printhead, is one of the system's most critical components, responsible for delivering the filament at the appropriate temperature and flow rate [3].

The heating zone within the extruder is where the filament reaches the target temperature and achieves the necessary viscosity for deposition. The temperature distribution within this zone significantly affects key print quality factors such as interlayer bonding, nozzle clogging and surface smoothness. In the existing literature, most studies addressing this region are based on experimental approaches while integrated computational models encompassing both geometric optimization and thermal behavior remain limited [4].

This study proposes a computational method for predicting the thermal profile within the heating zone of FDM printheads. The developed model considers essential process parameters such as filament diameter,

nozzle diameter, print speed and layer thickness and estimates the thermal energy demand based on filament feed rate. Numerical simulations were conducted using CAD Simulation and results were supported by parametric modeling and graphical representations of temperature velocity relationships.

The proposed approach enables engineering based decision making in printhead design, enhances thermal efficiency and provides a configurable framework that can be tailored to user specific printing needs. Existing studies on thermal behavior in FDM printheads often rely on single material investigations and predefined parameters. For instance, Tichý et al. (2022) employed a finite element model to simulate the temperature distribution for PLA only [5]. Similarly, Meiabadi et al. (2024) experimentally examined the effects of extruder temperature and print speed [6]. However, most of these studies are not computationally driven and exhibit limited generalizability across different materials and process scenarios.

| Authors and Year            | Paper Title                                                                                                                                                                  | Method                              | Main Findings                                                                                                         | Gaps in Literature                                                                        | Contribution of This Study                                                        |
|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Tichý et al., 2022 [5]      | Mathematical Modelling of Temperature Distribution in Selected Parts of FFF Printer during 3D Printing Process                                                               | Finite Element Method (FEM)         | Temperature distribution calculated for PLA material.                                                                 | Use of only PLA experimental approach.                                                    | A computational model for materials other than PLA is proposed.                   |
| Ramos et al., 2023 [7]      | Experimental and Numerical Investigations on Heat Transfer in Fused Filament Fabrication 3D Printed Specimens                                                                | Experimental and numerical analysis | Heat transfer with different infill structures was investigated.                                                      | Focused on infill structure effects; no analysis of the heating zone temperature profile. | Thermal energy requirements were analyzed based on filament feed rate.            |
| Meiabadi et al., 2024 [6]   | Experimental Investigation on the 3D Printing of Nylon Reinforced by Carbon Fiber through Fused Filament Fabrication Process                                                 | Experimental analysis               | Effects of extruder temperature and printing speed were analyzed.                                                     | Experimental study; lacks a computational model.                                          | A parametric computational model has been developed.                              |
| Kudus et al., 2023 [8]      | Effect of Print Bed's Heat Flow on Curling and Surface Roughness of FDM Printed ABS Sample                                                                                   | Experimental analysis               | Effect of print bed heat flow on curling and surface roughness.                                                       | Only focused on print bed heat; no information on extruder heating zone.                  | Extruder temperature and filament properties were considered.                     |
| Hira et al., 2022 [9]       | Numerical and Experimental Analysis of Optimal Nozzle Dimensions for FDM Printers                                                                                            | Experimental and numerical analysis | Effects of nozzle dimensions on print quality were analyzed.                                                          | Focused on nozzle dimensions; no analysis of heating zone temperature profile.            | Interaction between nozzle dimensions and heating zone was modeled.               |
| Vishwjeet et al., 2023 [10] | Effect of Infill Density, Infill Pattern and Extrusion Temperature on Mechanical Properties of Part Produced by 3D Printing FDM Technology Using ABS, PLA and PETG Filament  | Experimental analysis               | Infill density, pattern and extrusion temperature effects on mechanical properties.                                   | Focused on mechanical properties; no thermal profile analysis.                            | Thermal profile and mechanical properties relationship was investigated.          |
| Taheri et al., 2019 [11]    | A Novel Model for Thermal Behavior Prediction of Oil Immersed Distribution Transformers with Consideration of Solar Radiation                                                | Mathematical modeling               | Thermal behavior of oil immersed distribution transformers was modeled.                                               | No direct study on FDM printers.                                                          | Thermal behavior modeling approach adapted for FDM printers.                      |
| Akhoundi et al., 2020 [12]  | An Experimental Study of Nozzle Temperature and Heat Treatment (Annealing) Effects on Mechanical Properties of High Temperature Polylactic Acid in Fused Deposition Modeling | Experimental analysis               | Nozzle temperature and heat treatment effects were analyzed.                                                          | No detailed study on the effect of nozzle temperature on the heating zone.                | Interaction between nozzle temperature and heating zone was modeled.              |
| This work                   | A Computational Method for the Design of Heating Zones in FDM 3D Printer Extruders                                                                                           | Computational analysis              | Analyzes thermal energy and temperature profiles of the FDM 3D printer extruder heating zone based on key parameters. | Al models considering multiple parameters and materials for FDM extruder heating zones.   | A computational model to analyze thermal profiles in the FDM 3D printer extruder. |

## II. MATERIALS AND METHODS

The double pendulum is illustrated in Diagram1. It is convenient to define the coordinates in terms of the angles between each rod and the vertical. In this diagram  $m_1, L_1$  and  $\theta_1$  represent the mass, length and the angle from the normal of the inner bob and  $m_2, L_2$  and  $\theta_2$  stand for the mass, length, and the angle from the normal of the outer bob. The simple kinematics equations represent in next section to derive equations of motion by using Lagrange equations

In order to conduct thermal analysis of the heating zone within the extruder used in 3D printers, a simulation based methodology was employed. In the simulation scenarios, Acrylonitrile Butadiene Styrene (ABS) a commercially widespread filament material was selected as the base polymer. The material properties, such as density, specific heat capacity and thermal conductivity, were defined based on up to date data from the scientific literature [13,14].

For the structural components of the extruder, materials commonly utilized in FDM systems, as reported in the literature, were selected. Specifically, aluminum was chosen for the heating block, brass for the nozzle, stainless steel for the thermal break and PTFE (Teflon tubing) for insulation purposes [15]. Each material was modeled to reflect its actual application in operational systems and then integrated into the thermal simulations accordingly [16].

## 2.1 Theoretical Modeling Approach

In the design of the heating zone and the determination of its temperature profile, a volumetric flow rate based theoretical model was developed to estimate the amount of heat to which the filament is exposed as it passes through the extruder [17]. This model is based on the principle of continuous flow of solid filament through the nozzle and assumes that the heating requirement is directly related to the amount of material that must be melted within a given time interval [18].

The fundamental assumptions of the model are as follows: The flow is continuous and incompressible. Heat transfer within the filament occurs only by conduction and convection. The initial temperature of the filament is equal to the ambient temperature (approximately 25 °C). The specific heat capacity and density of the material are constant (applied for ABS) [19].

In the process of designing the heating zone and defining its temperature profile, a theoretical model based on volumetric flow rate was developed to estimate the amount of thermal energy absorbed by the filament as it passes through the extruder [17]. The model (Figure 1) assumes a continuous feed of solid filament through the nozzle and considers that the required heating energy is a function of the amount of material that must be melted within a given time interval [18].

The fundamental assumptions of the model are as follows: The flow is continuous and incompressible. Heat transfer to the filament occurs solely via conduction and convection mechanisms. The initial temperature of the filament is equal to the ambient temperature (approximately 25 °C). The specific heat capacity and density of the material are constant and in this study, values corresponding to ABS material were adopted [19].

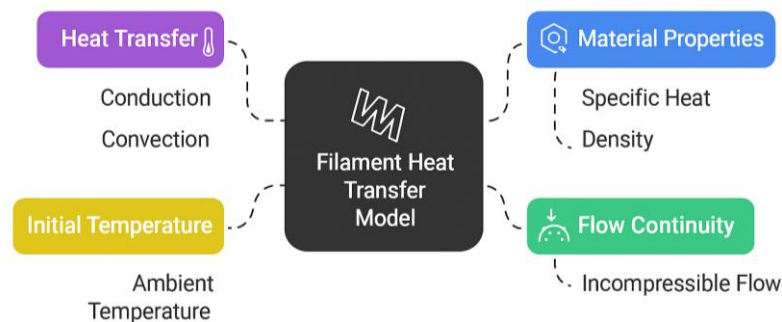


**Figure 1.** Basic assumptions of the filament heat transfer model

Based on the aforementioned assumptions, the thermal energy requirement  $Q$  during the extrusion process can be modeled by the following equation:

$$Q = \dot{m} \cdot c_p \cdot (T_{\text{target}} - T_{\text{initial}}) \quad (1)$$

where:

- $\dot{m}$  is the mass flow rate of the extruded filament (kg/s),
- $c_p$  is the specific heat capacity of the material (J/kg·K),
- $T_{\text{target}}$  represents the target melting or printing temperature of the filament (°C),
- $T_{\text{initial}}$  is the initial (ambient) temperature of the filament (°C).

The mass flow rate  $\dot{m}$  can be derived from the volumetric flow rate  $Q_v$  using the relation:

$$\dot{m} = \rho \cdot Q_v = \rho \cdot A_{\text{nozzle}} \cdot U_{\text{print}} \quad (2)$$

where:

- $\rho$  is the density of the filament material ( $\text{kg/m}^3$ ),
- $A_{\text{nozzle}}$  is the cross sectional area of the nozzle outlet ( $\text{m}^2$ ),
- $U_{\text{print}}$  is the linear velocity of the print head ( $\text{m/s}$ ).

By combining these expressions, the required thermal power for the heating zone can be calculated as a function of the printing parameters. This theoretical model serves as a foundation for defining initial boundary conditions in CAD Simulation analyses and enables the comparative evaluation of heating performance under varying print configurations [20].

## 2.2 Filament Feed Rate

A critical parameter in the thermal design of the extruder's heating zone is the filament feed rate, which refers to the actual velocity at which material advances through the extruder [21]. In practical applications, the term "printing speed" generally denotes the translational velocity of the print head. However, for accurately defining the thermal regime under various operating conditions, it is essential to determine the true extrusion velocity of the material discharged from the nozzle [22].

Accordingly, a method is proposed to calculate the filament feed rate based on key printing parameters that directly influence the extrusion process and are required for accurate estimation [18]:

1. Filament diameter: The most commonly used standard filament diameter is taken as  $D_{\text{fil}}=1.75$  mm.
2. Nozzle diameter: The typical nozzle diameter range in commercial FDM systems is between  $D_{\text{nozzle}}$  0.2 mm and 1.2 mm.
3. Layer height: This value is generally selected as a function of the nozzle diameter, with the recommended range being  $0.25 \div 0.75 \cdot D_{\text{nozzle}}$ .
4. Print head speed: The translational velocity of the print head varies within the range of  $U_{\text{print}}=25 \div 150$  mm/s [23].

This approach enables a more precise estimation of the actual filament movement within the extruder, which is critical for evaluating heat transfer efficiency and defining thermal loading in computational simulations.

## 2.3 Parametric Thermal Distribution Analysis Method

In this study, a mathematical formulation based on volumetric flow rate was developed to determine the temperature distribution within the heating zone of the extruder. The model calculates the amount of molten material exiting the nozzle under various printing parameters and transfers the resulting filament velocity data to the simulation environment to evaluate the corresponding temperature profiles within the extruder [4].

Thermal simulations were performed using CAD Simulation and the following parameters were defined as variables:

- Nozzle diameters: 0.2 mm, 0.4 mm, 0.8 mm
- Layer thicknesses: 0.1 mm, 0.2 mm, 0.3 mm
- Print head speeds 50 mm/s, 100 mm/s, 150 mm/s
- Convection type: natural convection and forced convection (airflow at 0.5 m/s)
- Filament material: ABS ( $\rho = 1040 \text{ kg/m}^3$ ,  $c_p \approx 1300 \text{ J/kg} \cdot \text{K}$ )
- Initial temperature: 25 °C
- Target heater temperature: 220 °C

Using these parameter sets, simulations were conducted to extract the temperature distribution across internal regions of the extruder and temperature profiles were obtained along the length of the heating zone. All simulations were conducted in the CAD Flow Simulation module. Material properties and boundary conditions were assigned based on values commonly accepted in the literature. Specifically, the density of ABS filament was considered within the range of  $1.03\text{--}1.14 \text{ g/cm}^3$ , with an average of  $1.06 \text{ g/cm}^3$  used in this study. The specific heat capacity ( $c_p$ ) of ABS was taken within the range of  $1.60\text{--}2.13 \text{ kJ/(kg} \cdot \text{K)}$  and the average value was selected accordingly. Thermal conductivity ( $k$ ) for ABS was defined within the literature range of  $0.14\text{--}0.21 \text{ W/(m} \cdot \text{K)}$  [24].

CAD Simulation was utilized to define the mass of the extruder components, heat transfer boundary conditions and thermal contact relationships based on the actual geometry. As a result, the filament's thermal

demand was analyzed in conjunction with nozzle geometry and progressive printing conditions, leading to the development of a valid and comprehensive thermal model.

## 2.4 Filament Velocity Calculation Formula

To determine the filament velocity, a volumetric flow based formulation commonly used in hydraulic and heat transfer calculations was employed [19]:

$$U_{fil} = (4 \cdot D_{nozzle} \cdot H_{layer} \cdot L_{print}) / (\pi \cdot D_{fil}^2) \quad (3)$$

This equation enables the estimation of the filament velocity within the heating zone of the extruder. By adjusting printing parameters and system settings, the dependency of filament motion on various process variables can be systematically analyzed [4].

## III. RESULTS AND DISCUSSION

The numerical data related to the temperature distribution are presented visually in Figure 2. These graphical representations include both the temperature variation along the central axis and the 2D thermal profile across the cross sectional plane of the heating zone. The findings reveal that the thermal design of the heating region should not be based solely on fixed temperature targets but rather must be optimized according to dynamic printing conditions.

As a result of the thermal analyses, the maximum, minimum and average temperatures for each set of printing parameters were calculated. Moreover, the variations in internal temperature within the extruder were graphically correlated with both filament feed rate and nozzle diameter, indicating a strong dependency between thermal performance and process conditions.

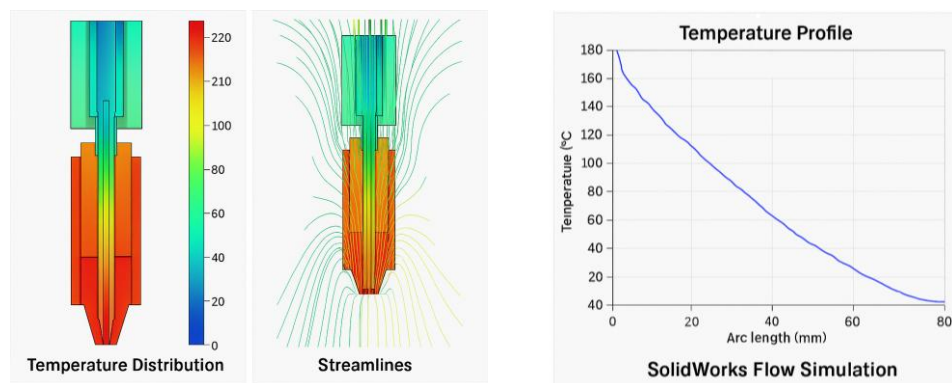


**Figure 2.** Temperature distribution and simulation of temperature profile

The numerical analyses revealed that the temperature distribution within the heating zone of the FDM 3D printer extruder is highly sensitive to printing parameters. In particular, an increase in nozzle diameter leads to a higher volume of extruded filament, thereby requiring greater thermal energy input. When comparing nozzle diameters of 0.4 mm and 0.8 mm, it was observed that the core region of the heating zone exhibited a temperature rise for the larger nozzle, whereas the outer layers experienced a notable temperature drop. This indicates that thermal uniformity becomes a critical design criterion in large nozzle applications.

When the print head velocity ( $U_{phv}$ ) was varied between 50 mm/s and 150 mm/s, the residence time of the filament within the heating zone decreased. As a result, the regions unable to reach the target temperature expanded and heat transfer from the surface toward the core became insufficient. This scenario reduces thermal transfer efficiency and may potentially lead to interlayer adhesion issues during printing.

Furthermore, under forced convection conditions (airflow at 0.5 m/s), the simulations showed a significant increase in heat loss through the outer surfaces of the system. Consequently, the output power of the heating element was found to play a decisive role in compensating for this loss.

Based on the performed calculations, the variation in extrusion temperature as a function of these parameters is illustrated in Figure 3.

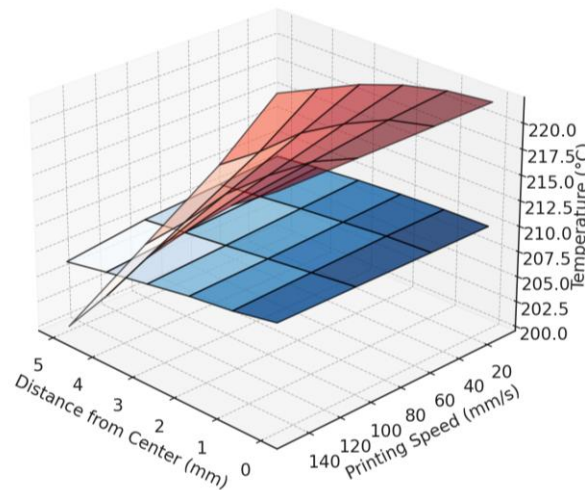


**Figure 3.** Thermal Distribution in FDM Extruder Heating Zone as a Function of Nozzle Diameter and Printing Speed

Figure 4 presents a graphical representation of how filament feed rate varies as a function of nozzle diameter. According to the analysis results, the feed rate increases proportionally with both layer height and printing speed. The graphical data indicate that this increase exhibits a linear trend. Specifically, at a layer height of 0.1 mm and a printing speed of 100 mm/s, the feed rate was measured at 4 mm<sup>3</sup>/s; under the same speed with a 0.3 mm layer height, the value increased to 12 mm<sup>3</sup>/s. Similarly, the maximum feed rate of 18 mm<sup>3</sup>/s was observed at a 0.3 mm layer height combined with a 150 mm/s printing speed.

These findings demonstrate that when high layer thickness and high printing speed are selected simultaneously, the extruder must operate under conditions of significantly higher volumetric flow rate. Therefore, it is concluded that during parameter optimization in FDM based manufacturing processes, the mechanical and thermal capabilities of the extruder system must be carefully considered.

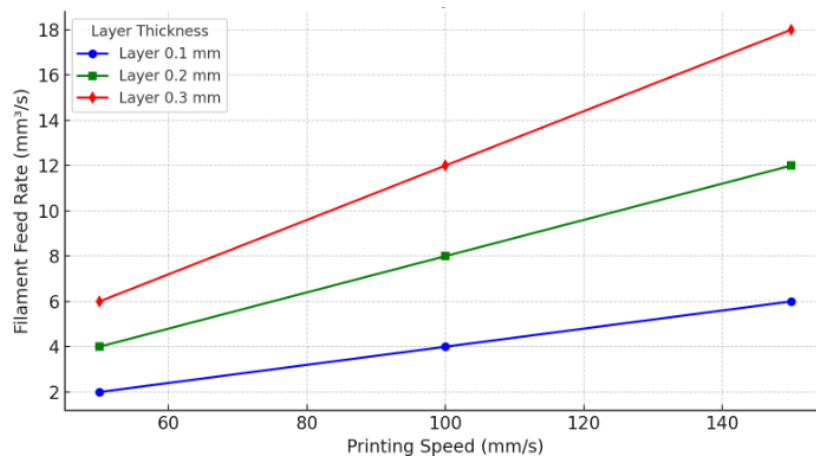


**Figure 4.** Effect of printing speed and layer thickness on filament feed rate in FDM printing

As a result of the modeling and optimization studies, an extruder design was developed (Figure 5). The cooling function is achieved by approximately five horizontally arranged aluminum fins, which limit heat transfer to prevent premature softening of the filament. A transition zone is located between the heatsink and the heating block and it is recommended that this region be manufactured from a material with low thermal conductivity to ensure effective thermal insulation.

The modular structure of the design allows for easy part replacement and upgrades. Effective thermal management is critically important for maintaining print quality and ensuring process reliability in FDM systems.

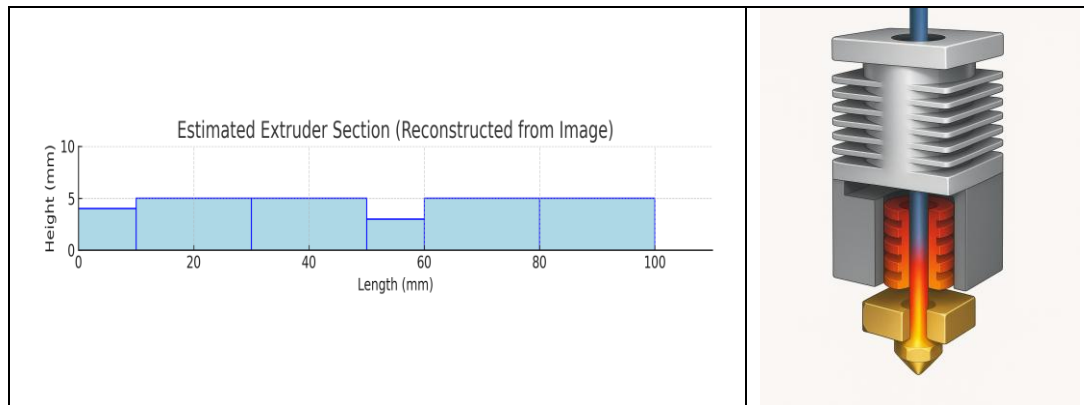


**Figure 5.** FDM Extruder Design

#### IV. CONCLUSION

In this study, a computational approach was developed to analyze the temperature distribution within the heating zone of extruders used in Fused Deposition Modeling (FDM). The proposed modeling and simulation framework is directly related to contemporary research themes such as thermal distribution, extrusion behavior, heat transfer modeling and nozzle design optimization. Through parametric analyses conducted in CAD Simulation, the thermal performance under varying printing parameters namely nozzle diameter, print speed and layer thickness was thoroughly investigated.

The simulation results revealed that increasing the nozzle diameter led to a higher volume of extruded filament, which in turn produced non uniform temperature gradients within the heating zone. Specifically, larger nozzles exhibited a rise in temperature at the core while outer regions experienced noticeable thermal drops. This finding highlights the need for geometrical and thermal optimization of the heating system, especially in high throughput printing applications, to mitigate thermal inconsistency.

Moreover, increasing the printing speed reduced the residence time of the filament in the heating zone, expanding regions that fail to reach the target temperature. This condition may negatively affect critical quality factors such as interlayer adhesion and layer bonding strength. Under forced convection scenarios, heat loss from the outer surfaces intensified, necessitating thermal rebalancing of the system to maintain energy efficiency.

Additionally, analyses based on printing specific variables such as volumetric flow rate, material feed rate and filament throughput demonstrated that feed rate increases linearly with both layer thickness and printing speed. At a layer thickness of 0.3 mm and print speed of 150 mm/s, the extruder operated at a high throughput of 18 mm<sup>3</sup>/s, indicating that extruder capacity, thermal loading and mechanical stress tolerance must be carefully considered.

In conclusion, the proposed computational methodology enables the engineering driven optimization of FDM extruder heating zones. The developed model contributes significantly to print quality, energy efficiency and system reliability while also offering a customizable design framework adaptable to user specific manufacturing requirements.

Future research could focus on extending the computational model to incorporate dynamic boundary conditions, such as ambient temperature variations and material dependent thermal behavior. Additionally, experimental validation is encouraged to enhance the predictive accuracy of the model. Investigating more complex extruder geometries and integrating the model into real time control systems could further improve the performance of FDM 3D printers, especially in high speed and large scale production settings.

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