Thermal study of clogging during filament-based material extrusion additive manufacturing: experimental–numerical study

Zahra Taheri1 · Ali Karimnejad Esfahani2 · Abas Ramiar1

Received: 11 March 2021 / Accepted: 23 October 2021 / Published online: 14 January 2022
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Abstract
One of the major drawbacks of material extrusion additive manufacturing (AM) is hot-end clogging. This study aims to answer the question, “How clogging happens and what thermal conditions lead to clogging during filament-based material extrusion?” Answering this question requires a clear understanding of temperature distribution inside the liquefier. However, this could not be achieved only through experimental measurements. Therefore, numerical simulations were also carried out by developing a 3D finite volume model of the hot-end. The results obtained from numerical simulations show good agreement with experimental measurements. They also give us a detailed picture of the temperature gradient near the nozzle. A series of experiments were performed to determine at what thermal conditions clogging occurs, and some criteria for avoiding clogging were presented. The temperature distribution of those thermal conditions that leads to clogging is then investigated numerically to analyze the clogging mechanism. As the results show, overheating the heat barrier increases the length of the filament, whose temperature is above the glass transition temperature. As this length exceeds a critical value, the filament buckles under the extruder motor force, and consequently clogging occurs.

Keywords Clogging · Multi-material printing · Material extrusion · Numerical simulation · Heat transfer · Buckling

1 Introduction
The global additive manufacturing (AM) market size has been growing steadily and is expected to reach USD 34.8 billion by 2024 [1]. During the AM process, the part is built layer by layer based on a computer-aided design (CAD) model. There are seven major branches of 3D printing techniques: vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination [2]. Material extrusion (also known as fused filament fabrication, FFF) is the most common method because the process is simple and incurs lesser manufacturing costs.

Despite the wide range of applications of this technique, such as rapid prototyping [3], art [4, 5], and medical fields [6–8], there are still some defects and process failures to overcome, like hot-end clogging, overflow, layer separation, or warping. Among them, hot-end clogging is one of the most important process failures [9].

Generally, the absence of enough space for extrusion or warping of the printing part can block the deposition of molten filament and consequently lead to clogging [10]. However, most of the time, clogging occurs due to blockage of filament path inside the hot-end. This may happen because of the presence of some dust or burnt filament inside the hot-end. In the case of filled polymers, the high filler content is also a possible factor that needs to be considered [11]. Other possible reasons for clogging in the FFF process are nozzle damage, breaking of filament, or presence of debris in the filament. However, the most common reason for nozzle clogging is inappropriate hot-end cooling, as nearly half of all E3D-v6 hot-end issues are related to this factor [12].

Considering the numerous reasons for nozzle clogging, two approaches have been adopted to study the clogging. The first approach focuses on nozzle condition monitoring to prevent clogging. There are many studies that have focused on using different types of sensors such as acoustic
emission (AE) sensors [13, 14], accelerometer sensors [15], optical cameras [16], and more, to in situ monitoring during the FFF process and prevent anomalies such as nozzle clogging. These sensors tend to generate a large amount of data. So, to handle them, using data-driven methods such as SVM [14, 17], HSMM [17, 18], compressive sensing [19], unsupervised density-based clustering method [20], least squares support vector machine (LS-SVM) [21], or other intelligent algorithms are necessary. Although these methods have shown to be an effective way to detect and prevent FFF process anomalies, they mainly concentrate on signal processing and machine learning techniques to analyze the data gathered from various sensors. In this way, some studies have focused on representing theoretical models to gain more detailed information from sensor signals [22, 23]. However, detecting and preventing the nozzle clogging condition, long before extreme nozzle blockage, remain a challenge, as little attention has been paid to the physics of the defect formation.

The second approach focuses on the clogging formation mechanisms and factors that can potentially lead to clogging. In this way, some research has focused on high feeding rate as a potential factor for clogging and proposed some limitations for maximum safe feeding rate [24–26]. However, these criteria do not consider the stiffness and geometry of the pushing feedstock. Some other studies have focused on the temperature distribution of the hot-end to investigate the possibility of clogging occurrence and improve the design [27, 28]. Also, one study has proposed that clogging occurrence shall be due to uneven temperature distribution in the liquefier components [29]. Another study investigated the possible effect of moisture on nozzle blockage [30]. In the case of filled filaments, a number of studies have been performed on the effects of different parameters such as filler size, polymer viscosity, or volume contents on clogging occurrence [11, 31].

This study adopts the second approach and aims to focus on hot-end thermal conditions that can lead to clogging as one of many reasons for clogging occurrence in the FFF process. For this purpose, thermal analysis of the hot-end is necessary. Much effort has been made to understand the melt flow and thermal behavior in the FFF process that can be categorized into three groups.

The first group of studies has focused on the extruded molten filament. In this way, some studies have investigated the effect of printing parameters on the exiting molten filament [32] or the quality of the deposited material [33]. Several investigations have studied the molten polymer between the moving printing head and the substrate [34, 35]. Some other research has studied the deposited material cross-section shape either for a strand [36–38] or in a multilayer print [39–41]. The effect of considering viscoelastic effects or solidification models is also studied in some of these research [42, 43]. Some researchers have mainly focused on the swelling effect during extrusion [44, 45], and in the case of fiber-filled polymers, several studies have concentrated on studying fiber orientation after deposition [45–47]. There are also some studies that have investigated the cooling history of the deposited material [48–50]. Furthermore, some literature has focused on thermal stresses induced due to shrinkages of different regions of the fabricated part [51–53]. Generally, this group of studies is more focused on the deposited material and assumes that filament comes out of nozzle tip without abnormalities which is not always the case.

The second group of studies has focused on melt flow and thermal study of melted filament inside the nozzle channel. In this way, some research has focused on the melt flow inside the nozzle to better understand the melting mechanism [54, 55], while some others have studied the feasibility of using new materials in the course of the FFF process [56]. Several studies have been performed to track changes in pressure and temperature inside the nozzle by innovative nozzle designs and direct measurements [57, 58]. Some studies have examined the penetration of the filament core at a temperature less than $T_g$ inside the nozzle by varying printing parameters [59–61] to determine the limiting conditions in the FFF process. Some other research has turned their attention to studying the effect of nozzle geometrical parameters on molten filament flow [62–66]. Most of these studies use CFD as a powerful tool since some material properties of molten filament inside the nozzle are challenging to be measured directly. However, these studies usually only model the nozzle and liquefier channel, not the heat barrier and the heat sink. Technically, this means that most of these studies assume the inlet filament is cold as it enters the nozzle, while it is not necessarily always the case. As this investigation shows, the filament warms up before it enters the nozzle, especially in clogging cases.

To investigate the temperature distribution along the filament path before it enters the nozzle, considering heat transfer of the hot-end and its thermal interaction with the environment is necessary. In this regard, the third group of studies has focused on thermal interaction between fan airflow and heat sink. Some have focused on understanding the relation between heat sink temperature distribution and fan airflow speed [67]. Some others have studied heat sink thermal performance in order to optimize its design [68–71]. In this group of studies, the focus is mainly on the temperature distribution along the heat sink and its changes in response to variation of airflow speed or heat sink geometry parameters. They do not consider the molten filament flow inside the nozzle or the depositing material.

From a thermal perspective, this study falls into the third group. However, it aims to go one step further and answer the question “how inappropriate cooling condition leads to
For this purpose, the temperature distribution along the heat sink has been investigated experimentally and numerically at various fan airflow velocities. The results show that considering the radiation heat transfer is vital to achieving a good agreement between numerical and experimental results, especially at low fan airflow velocities. In this way, some criteria have been proposed. Then, the thermal condition leading to clogging is determined experimentally, and the hot-end temperature distribution in that condition is investigated with the validated numerical model. The results show that in poor cooling conditions, the length of the filament inside the heat barrier, whose temperature is above the glass transition temperature, increases considerably, and based on a simple analytical evaluation, it buckles under the extruder motor force, which consequently clogs the hot-end. These studies are carried out for two different materials of ABS and PLA. The results show similar behavior.

The rest of the paper is organized as follows. The experimental setup and procedures are described in Section 2. The numerical model is presented in Section 3. The results of this study are discussed in Section 4 with three subsections. Section 4–1 focuses on thermal analysis of hot-end and comparing numerical results with the experimental data. In Section 4–2, the cooling condition needed to avoid clogging is discussed, and some practical criteria for PLA and ABS 3D printing are provided. Section 4–3 is devoted to studying the clogging mechanism by buckling analysis of the solid filament inside the heat barrier. Finally, a conclusion is presented in Section 5.

## 2 Experiments

### 2.1 Overview of the measurement setup

According to Fig. 1, the RepRap Diamond hot-end consists of 4 main components: a Diamond nozzle, a cooler shield, three E3D-Lite6 heat sinks including a heat barrier inside each of them, and a 50mm fan. A 40W cartridge heater heats the Diamond nozzle. It is maintained at the desired temperature by a control loop and a 100kΩ NTC thermistor that measures the nozzle temperature. Figure 2 shows the RepRap Diamond nozzle in detail.

A core x–y filament-based material extrusion printer, built by the authors, was used to study the thermal performance and the clogging phenomenon in the Diamond hot-end. Open-source Marlin firmware was uploaded to the MKS GEN V1.4 board. Four 100kΩ NTC thermistors were attached to the heat sink by Kapton tape to record the temperature along it. Figure 3 shows the configuration of the hot-end in the experiments. The more precise locations of the thermistors are illustrated in Fig. 4. The Repetier-Host V2.1.6 was selected as the machine control software to control the nozzle temperature, airflow velocity, and other printing parameters.

A FONSONING FSY50S12H fan was used, and its velocity was controlled by adjusting the voltage applied to the fan. The fan was connected to the fan terminal on the board to facilitate adjusting the fan input voltage by using the manual control tab in Repetier-Host, shown in Fig. 5. It should be noted that in the actual printing process, the heat sink cooling fan should not be connected to this terminal. Because it is dedicated to another fan used for cooling the freshly deposited material to provide a suitable base for the next layer [72]. Incorrect use of this terminal for heat sink cooling fan is one of the common causes of clogging in the actual printing process [12].

Percentage values of 15%, 20%, 30%, 40%, 50%, and 60% of board input voltage were applied, by varying the fan input voltage in Repetier manual control tab, as shown in Fig. 5. The board input voltage in this study was 12V. It should be noted that higher voltage percentages were avoided since further increasing the airflow velocity had little effect on the temperature distribution along the heat sink. This is mostly due to the dominance of forced convection that will be discussed later.

### 2.2 Temperature measurement experiments

Experiments were carried out to register the temperature at four points along the heat sink to compare them with the proposed numerical simulation implemented through the FVM.

The experimental procedure to study the temperature distribution along the heat sink was as follows:
Fig. 2 RepRap Diamond nozzle

Fig. 3 The configuration of the hot-end for experiments in this study
At the beginning of each test, the fan was turned on at the desired percentage of the input voltage.

- The ambient temperature was approximately 27°C, and the nozzle was heated to 210°C for the PLA, and 260°C for the ABS.
- The heat sink was left for at least 30 min to reach a stable thermal condition.
- Under stable conditions, temperature values obtained from the thermistors were recorded.

Experiments were repeated at least four times for all voltages and nozzle temperatures. Finally, the average of the results was calculated and reported.

### 2.3 Clogging detection experiments

Another set of experiments were carried out to investigate clogging occurrence at different airflow velocities. The airflow is thus taken as the variable of this study. These experimental results are then used alongside the numerical modeling to obtain the filament temperature distribution under clogging conditions.

A cube with dimensions of 15 mm × 15 mm × 20 mm was printed to investigate the impact of heat sink cooling conditions on the clogging phenomenon during the printing process.
process. The cube dimensions are small enough to avoid warping. Also, other factors that might lead to clogging, such as the presence of dust or burnt material inside the nozzle channel, insufficient space between the nozzle tip and printing bed [10], and too much retraction length and speed were controlled. The process parameters are shown in Table 1.

The clogging test steps were as follows:

- The ambient temperature was approximately 27°C. The first five layers were printed at maximum fan speed to ensure that other potential factors such as the presence of burnt filament and dust did not cause clogging.
- After the first five layers, the fan voltage was adjusted to the desired value for that test.
- The printing process was monitored precisely. There were three different scenarios: (1) complete clogging, (2) no complete clogging but with some problems, and (3) the printing process without any problem. Whenever clogging was identified, the operation was stopped, and the hot-end was cleaned for the next experiment.
- These experiments were also repeated four times for all fan voltages.

3 Numerical simulation

As shown in Fig. 6, a 3D model was developed to analyze the Diamond hot-end numerically and determine the temperature distribution of filament inside the heat barrier, as it is crucial in the study of clogging. The hot-end geometry shows a rotational periodicity of 120°, bringing about a significant reduction of modeled volume and computational costs. The model consists of six different domains: a Diamond nozzle made of brass, a heat barrier made of stainless steel, an E3D-Lite6 heat sink made of aluminum, a Diamond cooler shield printed with ABS filament, a feedstock filament of ABS or PLA, and an air domain.
3.1 Governing equations

Numerical simulation of Diamond hot-end heat transfer was performed by considering conduction, convection, and radiation heat transfer. The general governing equations for the problem in the stationary state are defined at [74]. The continuity (Eq. 1) and Navier-Stokes (Eq. 2) equations were solved for the fluid region, while the energy equation (Eq. 3) was solved for both fluid and solid regions. These equations are solved taking into account that our analysis was performed in the steady-state condition, and there was no mass or heat generation:

\[ \nabla \cdot (\rho \vec{v}) = 0 \quad (1) \]

where \( \rho \) is the fluid density and \( \vec{v} \) is the fluid velocity.

\[ \nabla \cdot (\rho \vec{v}) = -\nabla p + \nabla \left( \mu \left( \nabla \vec{v} + (\nabla \vec{v})^T \right) - \frac{2}{3} \mu (\nabla \cdot \vec{v}) I \right) + \rho \vec{g} \quad (2) \]

where \( p \) is the fluid pressure, \( \mu \) is the fluid dynamic viscosity, \( I \) is the unit tensor, and \( \rho \vec{g} \) is the gravitational force.

\[ \rho C_p \nabla T = \nabla (k \nabla T) \quad (3) \]

where \( C_p \) is the thermal capacity, \( k \) is the thermal conductivity, and \( T \) is the temperature. Note that, as the Brinkman number is quite small, energy transfer through viscous dissipation was neglected.

The \( k-\epsilon \) turbulence model was used to capture any turbulence in the airflow field. This model yields good accuracy in the absence of large adverse pressure gradients [75], while using just two transport equations.

In this study, the Discrete Ordinate (DO) model was used to model the radiation effects. As a beam of radiation travels through a medium, it may lose energy because of medium absorption, gain energy from medium emissions, or its energy may be increased or decreased by medium scattering. The differential form of radiative transfer equation (RTE) for a beam in the direction \( \vec{s} \) and position \( \vec{r} \) can be written as [74]:

\[ \frac{dt(\vec{r}, \vec{s})}{ds} + (a + \sigma_s) I(\vec{r}, \vec{s}) = \frac{a \sigma T^4}{\pi} + \frac{\sigma_t}{4\pi} \int_0^{4\pi} \phi(\vec{r}, \vec{s}, \vec{s}') d\Omega' \]  \( (4) \)

where \( \vec{r} \) is the position vector, \( \vec{s} \) is the direction vector, \( \vec{s}' \) is the scattering directional vector, \( s \) is the path length, \( a \) is the absorption coefficient, \( n \) is the reflective index, \( \sigma_s \) is the scattering coefficient, \( \phi \) is the phase function, \( \Omega' \) is the solid angle, and \( I \) is the radiation intensity. \( \sigma \) is the Stefan-Boltzmann constant and equal to \( 5.67 \times 10^{-8} W/m^2K^4 \).

DO transforms RTE into a set of simultaneous partial differential equations. In the DO model, the equation of RTE (Eq. 4) is solved for a set of discrete directions that covers total angular space \( 4\pi \) sr. So that each octant of angular space was discretized to 4 polar angles \( (N_\theta) \) and 4 azimuthal angles \( (N_\phi) \), which means \( 8 \times 4 \times 4 \) solid angles. All solid angles were divided into \( 3 \times 3 \) pixels. All surfaces were assumed to be opaque, diffuse, and gray.

3.2 Boundary conditions

As previously mentioned, only one-third of the geometry was modeled in the simulation. Figure 7 shows the adopted boundary conditions.

The gauge pressure at the pressure outlet boundaries (Fig. 7a) was considered to be zero, as it was sufficiently far from the main flow stream. The static temperature at these boundaries was equalized with the ambient temperature \( 27^\circ C \). The internal emissivity for all of these boundaries was assumed to be 1.

The no-pressure-drop periodic boundaries (Fig. 7b) used in this study imply that velocity components repeat themselves as follows:

\[ u_r(r, \theta, z) = u_r(r, \theta + \frac{2\pi}{3}, z) = u_r(r, \theta + \frac{4\pi}{3}, z) \]
\[ u_\theta(r, \theta, z) = u_\theta(r, \theta + \frac{2\pi}{3}, z) = u_\theta(r, \theta + \frac{4\pi}{3}, z) \]
\[ u_z(r, \theta, z) = u_z(r, \theta + \frac{2\pi}{3}, z) = u_z(r, \theta + \frac{4\pi}{3}, z) \]  \( (5) \)
The same applies to the temperature.

\[ T(r, \theta, z) = T\left(r, \theta + \frac{2\pi}{3}, z\right) = T\left(r, \theta + \frac{4\pi}{3}, z\right) \quad (6) \]

The fan airflow was modeled by velocity inlet boundary condition (Fig. 7c).

As the nozzle temperature is continuously controlled at the desired temperature by the thermistor within the feedback loop, the constant temperature of 210°C for PLA, and 260°C for ABS was considered for the Diamond nozzle domain.

In conjugate boundaries, equality of the temperature and heat flux for corresponding cells on the boundaries were provided.

### 3.3 Mesh study

A mesh convergence study was performed to ensure that obtained results are independent of mesh discretization. Four different mesh sizes were tested and brought in Table 2. Mesh 2, shown in Fig. 8, was used throughout the study as it provided a good compromise between accuracy and computational costs. Increased mesh resolution produced negligible changes in the temperature values (the variable of interest), while in lower resolution (Mesh 3), slight inaccuracies were observed.

### 4 Results and discussion

To study the thermal conditions leading to clogging, comprehensive knowledge about temperature changes in the hot-end is essential. Although experiments can give us reliable results about the temperature distribution along the heat sink, they cannot give a detailed picture of the temperature distribution in the heat barrier and the filament inside of it. Therefore, the necessity of numerical simulation becomes more evident. In the following, the heat sink temperature distribution obtained from numerical simulations is first compared with the experimental results at zero and then at non-zero fan airflow velocities in Section 4.1.1 and 4.1.2, respectively, to check their agreement with experimental measurements described in Section 2–2. The contribution of radiation heat transfer is also investigated in both cases.

In addition to the need for an appropriate numerical model, it is also necessary to experimentally determine the thermal conditions that lead to clogging. This is addressed in Section 4.2. Finally, using the numerical simulation and the results of Section 4.2, the clogging mechanism is studied by buckling analysis of the solid filament inside the heat barrier.

#### 4.1 The hot-end thermal analysis

##### 4.1.1 Heat sink thermal analysis at zero airflow velocity

Although the amount of voltage applied to the fan was known in each of the experiments, the value of the fan airflow velocity resulting from the applied voltage was not known except when the fan was off, and the fan airflow velocity was zero. Therefore, the zero-velocity condition is of high importance to evaluate the numerical simulation. However, it seems this condition has not been considered earlier with the justification that turning off the fan is not recommended in the actual printing process [67].

The study of the zero-airflow condition illustrates the significance of considering radiation heat transfer. Four different nozzle temperatures of 100°C, 125°C, 150°C, and 200°C were considered for investigating the zero-airflow velocity condition to validate our numerical simulation.

Figure 9 shows the comparison of the heat sink temperature distribution resulted from numerical simulations with experimental measurements in the zero-velocity condition at four different nozzle temperatures.

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**Table 2** The number of elements in the four different meshes used in this study

| Mesh number | Number of elements |
|-------------|--------------------|
| Mesh 1      | 2,943,883          |
| Mesh 2      | 1,792,806          |
| Mesh 3      | 853,729            |
| Mesh 4      | 456,380            |

Fig. 8 A section of the selected mesh for this study
Fig. 9 Comparing experimental temperature values along the heat sink with the temperature values obtained from the numerical simulation at zero airflow velocity condition (when the fan is turned off) at four nozzle temperatures of 100°C, 125°C, 150°C, and 200°C.

Table 3  Equivalent airflow velocity of each fan applied voltage

| Percentage of input voltage to the board applied to the fan | Voltage applied to the fan (V) | Equivalent velocity obtained from simulation (m/s) |
|----------------------------------------------------------|-------------------------------|-----------------------------------------------|
| 60% 50% 40% 30% 20% 15%                                  | 7.2 6 4.8 3.6 2.4 1.8         | 0.649 0.571 0.445 0.289 0.112 0.048           |
As the figure shows, there is a good agreement between the numerical results and the experimental measurements when the radiation model is included. But neglecting the radiation heat transfer in numerical simulations adversely affects the results to the extent that it causes an error of up to $17^\circ C$ at the nozzle temperature of $200^\circ C$. However, it is expected that this error will be reduced at higher fan airflow velocities (this will be discussed below).

4.1.2 Heat sink thermal analysis at non-zero airflow velocities

Different airflow rates were created for the experimental investigation of non-zero velocity conditions by applying different voltages to the cooling fan. Then, by comparing the experimental measurements of the heat sink temperature with the numerical results, the cooling airflow velocity was obtained for each applied voltage according to Table 3.

Finding equivalent velocities is essential because presenting the results in terms of fan voltages is useless unless the cooling fan is exactly similar to the one used in this study.

Figure 10 illustrates the temperature distribution along the heat sink obtained from experimental measurements and numerical simulations for PLA and ABS printing processes (nozzle temperatures of $210^\circ C$ and $260^\circ C$ respectively). Aside from good agreement observed between numerical and experimental results, Fig. 10 demonstrates that by increasing the fan airflow velocity, we reach a point that further increase in air velocity does not cause much change in the heat sink temperature distribution. This is the main reason why further voltage percentages were not studied.

Figure 11 shows the air velocity vectors around the hot-end at two different fan airflow velocities of $0.048 m/s$ and...
At the airflow velocity of 0.048 m/s, the contribution of forced convection in heat transfer is negligible, and the heat sink temperature is high compared to the surrounding temperature. Therefore, the convection and radiation heat transfer rates are comparable. According to Fig. 11b, increasing the airflow velocity to 0.571 m/s and enhancing forced convection heat transfer cause a significant reduction in the heat sink temperature and its difference with the surrounding temperature. So, the effect of radiation heat transfer is expected to be negligible at higher airflow velocities.
In order to determine precisely when the radiation heat transfer can be ignored, the effect of considering radiation heat transfer in numerical simulations at different fan airflow velocities was investigated for both PLA and ABS printing processes. As Fig. 12 shows, for air velocities of 0.2 m/s and greater, radiation heat transfer can be safely neglected with no considerable effect on the heat sink temperature distribution.

4.1.3 Correlation of fan air velocity and heat sink temperature

As presented in Table 3, based on the numerical simulations that proved to have a very good agreement with the experimental results, fan air velocities were determined. In order to present a correlation to predict the heat sink temperature based on the fan airflow velocity, thermistor 4, shown in Fig. 4, was selected as it was easier to measure in practical conditions.

Correlations (7) and (8) express the heat sink temperature at thermistor 4 in terms of fan airflow velocity for ABS and PLA printing processes, respectively.

\[
T_{4,\text{ABS}} = 63.2 \exp(-8.74 V) + 46.5 \exp(-0.26 V) \tag{7}
\]

\[
T_{4,\text{PLA}} = 45.5 \exp(-9.53 V) + 47.4 \exp(-0.41 V) \tag{8}
\]

In which, \( V \) is the fan airflow velocity in m/s.

Figure 13 shows the correlations (7), (8), and experimental measurements obtained from thermistor 4. As the figure shows, the derived correlations have high accuracy in predicting the heat sink temperature at all fan airflow velocities. Considering the precision of the correlations, they can be used to determine the unknown fan airflow velocity by measuring the temperature at the specified point. Also, Fig. 13 can be used to interpolate the fan airflow velocity with acceptable accuracy when the nozzle temperature is in the range of 210 to 260°C. Moreover, the result obtained in Fig. 10 is again evident here that increasing the fan airflow velocity will not always decrease the heat sink temperature significantly, and for fan velocities greater than 0.45 m/s, it only increases energy consumption.

4.2 Clogging detection and prevention

So far, the numerical model has been presented, and it has been shown how well it could predict the temperature distribution in different cooling conditions. In this section, the thermal conditions that lead to clogging are determined through the experiments described in Section 2.3. The experiments led to one of the following three conditions:

1. Complete clogging: in such cases, the heat barrier was completely blocked, as shown in Fig. 14a. In this condition, unclogging the hot-end was only possible by stopping the printing process and cleaning the nozzle and heat barrier. The process had to be re-started from the beginning. The “×” mark indicates this condition in Tables 4 and 5.

![Fig. 13 Experimental results of the heat sink temperature at Thermistor 4 and derived correlations from them in terms of the fan airflow velocity for ABS and PLA.](image-url)
2. No complete clogging, but with some problems: in this case, the filament could not be fed because a part of the filament inside the heat barrier was swelled due to high temperature and stuck to the inside wall of the heat barrier (Fig. 14a). Unlike the complete clogging condition, there was no need to stop the entire printing process. Instead, the process had to be paused to pull out the filament and cut off the swollen part. The “∗” mark represents this condition in Tables 4 and 5.

3. The printing process without any problem: The “✓” mark indicates this condition in Tables 4 and 5.

As Table 4 shows, for the PLA printing process, the complete clogging occurred when the fan air velocity was 0.112 m/s. Table 4 also shows that the second scenario mentioned above occurred in two experiments at 0.289 m/s. So, the airflow velocity of 0.445 m/s is considered the lowest possible airflow velocity that can be used reliably in this study. At this fan airflow velocity, according to correlation (8), the temperature at thermistor 4 is about 40°C that can be considered as a criterion under practical conditions.

As can be seen in Table 5, in the ABS printing process, the clogging only happened when the fan airflow velocity was decreased to 0.048 m/s. Therefore, to avoid clogging, the airflow velocity of 0.112 m/s seems sufficient. In this case, according to correlation (7), the temperature at thermistor 4 is about 69°C that can be used as a criterion under practical conditions. It should be noted that under this condition, as shown in Fig. 10, the temperature distribution along the heat sink is in the range of 69 to 73°C that is higher than the $T_g$ of PLA. Therefore, if the Diamond hot-end cooler shield is made of PLA or other materials with similar $T_g$, higher airflow velocities should be considered to prevent thermal damages.

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**Table 4** Clogging experiment results for PLA. Each specified condition repeated four times

| Fan airflow velocity (m/s) | 0.571 | 0.445 | 0.289 | 0.112 |
|---------------------------|-------|-------|-------|-------|
| Temperature at thermistor #4 (°C) | 37.7 | 40.1 | 45.0 | 60.9 |
| Test number 1 | ✓ | ✓ | ✓ | ✕ |
| Test number 2 | ✓ | ✓ | ✓ | ✕ |
| Test number 3 | ✓ | ✓ | * | ✕ |
| Test number 4 | ✓ | ✓ | * | ✕ |

**Table 5** Clogging experiment results for ABS. Each specified condition repeated four times

| Fan airflow velocity (m/s) | 0.445 | 0.289 | 0.112 | 0.048 |
|---------------------------|-------|-------|-------|-------|
| Temperature at thermistor #4 (°C) | 42.7 | 48.2 | 68.9 | 87.5 |
| Test number 1 | ✓ | ✓ | ✓ | ✕ |
| Test number 2 | ✓ | ✓ | ✓ | ✕ |
| Test number 3 | ✓ | ✓ | ✓ | ✕ |
| Test number 4 | ✓ | ✓ | ✓ | ✕ |
As the experimental results show, in the ABS printing process, the clogging occurs in lower fan airflow velocities in comparison with PLA. This is because ABS glass transition temperature ($T_g$) is higher than PLA. The comparison of ABS and PLA clogging suggests that, despite the difference in thermal and mechanical properties, both materials show a relatively same behavior. In both, clogging occurs suddenly as the fan air velocity gradually decreases. This may be related to the fact that the elastic module of both materials suddenly drops as the temperature passes the glass transition temperature. [76, 77]. Investigating this issue needs a detailed view of the temperature distribution of filament in the heat barrier, which is discussed in Section 4–3.

**Fig. 15** The temperature contour of the filament inside the heat barrier at three different fan airflow velocities. In the clogging cases, the length increases considerably.
4.3 Clogging mechanism

In this section, the numerical model results and the clogging experiments are combined to investigate the hot-end temperature distribution when the clogging occurs. This makes it possible to study the clogging phenomenon from a thermal perspective.

In material extrusion additive manufacturing, the pressure required to extrude the molten material is provided by the solid filament above it. In fact, the unmelted filament inside the heat barrier acts as a piston and pushes the molten filament through the nozzle. Figure 15 shows the temperature distribution of the filament inside the heat barrier for the ABS and PLA printing processes at three different airflow velocities. According to this figure, when airflow velocity decreases, the heat barrier overheats and causes the length of the filament, whose temperature is higher than the glass transition temperature, to increase. Therefore, under the stepper motor’s driving force, this filament cannot play its role and, instead, it buckles. Figure 16 shows the part of the filament pulled out of the heat barrier after the clogging occurred, and it well illustrates the condition described.

The force applied by the extruder motor to the filament, \( F_m \), can be determined by knowing the pressure drop in the nozzle, \( \Delta P \).

\[
F_m = \Delta P \times A_f
\]  

In which, \( A_f \) is the filament cross-section area. The pressure drop in a tube with length \( L \) and radius \( r \) is given by [78, 79].

\[
\Delta P = \frac{8\mu QL}{\pi r^4}
\]  

In which \( \mu \) is the viscosity at nozzle temperature which is approximately 100Pa.s for PLA [80] and 350Pa.s for ABS [81] assuming that the shear rate in the nozzle is about 575s\(^{-1}\) [82] and \( Q \) is the flow rate and can be roughly calculated as follow:

\[
Q = H_i \times W_i \times V_p
\]  

In which \( H_i \) is the layer height, \( W_i \) is the layer width, and \( V_p \) is the print velocity. This pressure is applied through the solid part to the melted material. On the other hand, the critical buckling load for elastic columns is given by [83]:

\[
F_{\text{buckling}} = \frac{\pi^2 EI}{(L_e)^2}
\]

In which, \( E \) is the elastic modulus of the material, \( I \) is the second moment of area, \( L_e \) is the column effective length which in the case of both ends pinned, the value would be \( L_e = \frac{L}{2} \). The critical length can be calculated from Eqs. 9 and 12:

\[
L_{\text{crit}} = \sqrt{\frac{\pi^2 ER^2}{4(\Delta P)}}
\]

In which \( R \) is the filament radius.

It should be noted that Eq. 13 can only give a rough approximation of the critical length \( L_{\text{crit}} \) mainly because it assumes the behavior of the material to be quite elastic. Also, the module values for both PLA and ABS were considered constant at the average temperature of that region and obtained from the literature [76, 77]. However, the calculated \( L_{\text{crit}} \) still shows a relatively good match with the experimental and numerical simulation results.

For different cooling conditions, the length \( L \), as shown in Fig. 15, was obtained from numerical simulations and compared with critical length \( L_{\text{crit}} \). For the ABS printing process, as illustrated in Fig. 17, by decreasing the fan airflow velocity to around 0.048m/s, the length \( L \) increases so that it exceeds the critical length calculated from Eq. 13, and eventually, it buckles and clogs the hot-end. This is entirely in agreement with the experimental results presented in Table 5.

A similar analysis can be applied to the PLA printing process. Figure 18 shows the length \( L \) resulted from numerical simulations at different fan airflow velocities for the PLA printing process. Similarly, when the length \( L \) exceeds the critical length \( L_{\text{crit}} \), the clogging happens, which is in agreement with the experimental results presented in Table 4. Interestingly, Fig. 18 suggests that the second scenario that happened in airflow speed of 0.289m/s in the PLA printing process can be explained by the closeness of the length \( L \) and \( L_{\text{crit}} \).
The analogous thermal behavior of two different thermoplastics of PLA and ABS in terms of clogging suggests that when the length \( L_{\text{crt}} \) exceeds the critical length \( L_{\text{crt}} \), the filament will buckle in this region. This seems to be one of the main clogging mechanisms in the FFF process of thermoplastics under inappropriate hot-end cooling conditions. Our rough estimate of the critical length \( L_{\text{crt}} \) in both ABS and PLA printing processes matches well with the experimental observations and numerical results, although more research needs to be done in this area to determine more precise value of \( L_{\text{crt}} \).

Moreover, since the heat sink and the heat barrier geometry in the Diamond hot-end are similar to those in E3D hot-ends, the same analysis about clogging occurrence can be applied to them. Also, the practical criteria of 40°C and 69°C presented for \( T_d \) to prevent clogging in the printing process of PLA and ABS, respectively, still give a good approximation for E3D hot-ends. However, the input airflow velocities corresponding to those temperatures may differ.

5 Conclusion

The temperature distribution along the filament path inside the hot-end was investigated numerically, and some experimental observations and measurements were carried out to investigate the question “how inappropriate cooling condition leads to clogging?” A core x–y filament-based material extrusion 3D printer constructed by authors was equipped with a RepRap multi-material Diamond hot-end. The heat sink temperature distribution was measured in a wide range of airflow rates for both PLA and ABS. Also, a series of experiments were performed by printing a cube of 15mm × 15mm × 20mm dimensions under different airflow velocities, and clogging occurrence was investigated.

The numerical simulation results were in good agreement with experimental data in the whole air velocity range. Based on thermal numerical modeling of hot-end and experimental results, the effect of inappropriate cooling on clogging occurrence was investigated. The derived conclusions of this study can be summarized as follows:

- Numerical simulation of the Diamond hot-end agreed well with experimental results. The study of the effects of radiation heat transfer showed that for air velocities of 0.2m/s and greater, radiation heat transfer could be safely neglected as it had no considerable effect on the heat sink temperature distribution. However, in lower cooling airflow velocities, this heat transfer mechanism cannot be ignored.
• Mathematical correlations for predicting the heat sink temperature were presented. For both PLA and ABS printing processes, the temperature at a certain point in the upper part of the sink (location of thermistor 4, as a convenient place for practical measurements) was presented in terms of cooling airflow velocity.

• In both PLA and ABS printing processes, as the airflow velocity increases, the heat sink temperature decreases steadily. But for velocities more than 0.45 m/s, while the power demand increases, no significant change in the sink temperature was observed.

• To avoid clogging in the Diamond hot-end, the maximum heat sink temperature in its upper part (thermistor 4) should be less than 40°C for PLA (equivalent to the fan airflow velocity of 0.445 m/s or more) and less than 69°C for ABS printing process (equivalent to the fan airflow velocity of 0.112 m/s or more). Due to geometrical similarities, these temperature criteria can also be considered a good approximation for other similar hot-ends like E3d hot-ends.

• Experimental and numerical studies on both PLA and ABS printing processes revealed that the clogging problem depends on the length of the filament, whose temperature is higher than the glass transition temperature. When this length exceeds the critical length, the filament buckles under the extruder force and clogging occurs. This conclusion may be generalized to other thermoplastics, while more investigations are needed to confirm it.

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