A study of the influence of external factors on the temperature control process of a 3D printer head in FDM technology

Abstract. The aim of the research presented in this article is to examine the influence of measurable external parameters and non-directly measurable disturbances on the amount of thermal energy emitted by the printer head. The research took into account the influence of the temperature inside the printer chamber and the plasticizing temperature of the material in the head on the amount of electricity consumed when controlling the temperature with the PID algorithm with parameters ensuring the value of the control error below 3°C. The summary presents a generalized level of influence of individual parameters, which gives clear indications which of them should be taken into account and measured during the construction of complex temperature regulators for 3D printers (concerns project no. POIR.01.01.01-00-2064/15).

Keywords: Additive manufacturing, 3D printing, FDM technology, Temperature regulation

Introduction

3D printing in FDM technology [1] (Fused Deposition Modeling) or otherwise called FFF (Fused Filament Fabrication) is one of the Rapid Prototyping methods - it is intended to produce parts of production quality in a relatively small number, if desired, at a relatively low cost, taking into account the cost of unit production of other manufacturing techniques [2]. However, the continuous development of this technology and its increasing popularity implies more and more attempts to use 3D printing in FDM technology for production applications where requirements for the product are precise and it is not possible to apply "concessions" which can be used in the case of prototyping. The key parameter influencing the overall quality, combining both visual (visible defects, artifacts) and technical features (strength, roughness) is the temperature in the printing head – a place where the material is heated and transitioned from solid to liquid phase.

Currently, in FDM printers, the temperature control mainly uses classic PID or bang-bang algorithms, which are most effective in stationary systems, to which the 3D printer head does not belong due to the multitude of measurable and non-directly measurable factors affecting the reception of thermal energy from the heating block. The aim of this article is to present results of the study of their influence on the amount of thermal energy consumed by the printer head during the PID algorithm control. The developed conclusions from these studies are significant in the context of working on algorithms improving the quality of temperature control in the head, and thus the above-described print quality.

The photos below (Fig. 1, Fig. 2) show an exemplary printout in two variants: produced in the correct temperature conditions (in the photos on the right) and defective due to incorrect temperature in the printer head during operation (in the photos on the left).
Research assumptions

a) Models were selected and a G-Code was prepared for subsequent main tests - temperature course measurements:

-Overview of the models in terms of ranges of material flow speed through the head for various types of printers (desktop and industrial standard). The process of determining the histogram of these values will consist of the analysis of 4,324,800 lines of code for selected models printed on standard size 3D printer - ATMAT Signal device and 2,346,800 lines of code for models printed in new technology for big volume 3D printers. The test will consist of extruding a certain amount of material at random speed through the generated sequence (a sequence of movements with random displacement and random speed, values will be generated so that their histogram is consistent with the Gaussian distribution with the average value and standard deviation obtained when testing the models, assuming that negative flows - retraction - are not taken into account).

-Generating G-Code for both tests: it was assumed to generate a course that allows: extruding 10g of PLA and a volumetric PETG equivalent (which is 3460 [mm] of filament with a diameter of 2.85 [mm]) at random speed with normal distribution with previously obtained parameters \( \mu = 330,2 \, [\text{mm} \, / \, \text{min}] \), \( \sigma = 137 \, [\text{mm} \, / \, \text{min}] \) using the ATMAT Signal printer, and a second course, which will allow extruding of 100g of PLA and the volumetric equivalent of PA6 (which is 13050 [mm] of filament with a diameter of 2.85 [mm]) at random speed with normal distribution with previously obtained parameters \( \mu = 1924,1 \, [\text{mm} \, / \, \text{min}] \), \( \sigma = 492,9 \, [\text{mm} \, / \, \text{min}] \) using the new print head design and control algorithms (referred further as "Research subject").

b) Defining the course of research:
- Determining starting conditions of the process: measurement will start no earlier than 5 minutes after conditions in the printer stabilize.
- Selection of materials: 3 materials of the Polymaker brand were selected

### Table 1. Material parameters comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Min. nozzle temp [°C]</th>
<th>Max. nozzle temp [°C]</th>
<th>Melting temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PolyLite™ PLA</td>
<td>190</td>
<td>230</td>
<td>150</td>
</tr>
<tr>
<td>PolyMax™ PETG</td>
<td>230</td>
<td>240</td>
<td>no data</td>
</tr>
<tr>
<td>Polymaker N600 PAS</td>
<td>280</td>
<td>300</td>
<td>215</td>
</tr>
</tbody>
</table>

- Determination of measurement points and recorded parameters - the following will be recorded: head temperature, theoretical value of material flow based on the extruder drive position, the amount of energy supplied to the head via the heater - 100% efficiency and completely resistive nature of the heaters are assumed. The following measurement points were assumed:

### Table 2. Test conditions

<table>
<thead>
<tr>
<th>Printer</th>
<th>Head temperature [°C]</th>
<th>Table temperature [°C]</th>
<th>Chamb. temperature [°C]</th>
<th>Material</th>
<th>Nozzle diameter [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATMAT Signal</td>
<td>190</td>
<td>30</td>
<td>30</td>
<td>PLA</td>
<td>0.8</td>
</tr>
<tr>
<td>ATMAT Signal</td>
<td>210</td>
<td>30</td>
<td>30</td>
<td>PLA</td>
<td>0.8</td>
</tr>
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</tr>
</tbody>
</table>

- Selection of algorithms allowing to reduce the studied courses to interpretable data set. Registering the amount of delivered energy will be done by numerical integration of the heater's power using the Simpson method. The heater power sampling frequency is 10Hz.
- Preparing test stands for testing in isolated conditions.

- Adapting the printer drivers to record data needed to conduct tests - continuous recording of previously defined parameters - generating a record with a frequency of 10Hz of the following parameters: heater power (PWM signal value), material flow speed (extruder drive speed), head temperature.
- Measuring and regulating temperature of important printer elements - temperature on the printer table will be regulated by a thermostat coupled with a duct heater.
- Tuning the head PID controller so that the absolute value of temperature deviation in the entire tested operating range does not exceed 3°C.

Results:

Below are presented the energy consumption graphs, divided into 4 graphs of the energy consumption growth during extrusion:

### Table 3. Energy consumption, PLA melting in nozzle 0.8mm

<table>
<thead>
<tr>
<th>PLA through 0.8mm nozzle (fig. 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETG through 0.8mm nozzle (fig. 4)</td>
</tr>
<tr>
<td>PLA through 2.5mm nozzle (fig. 5)</td>
</tr>
<tr>
<td>PA through 2.5mm nozzle (fig. 6)</td>
</tr>
</tbody>
</table>

![Fig. 3. Energy consumption, PLA melting in nozzle 0.8mm](image)
Additionally, a graph of an interpolated percentage increase in energy demand at a constant temperature in the printer chamber was presented. When generating the course, a simplification was adopted - the influence of the type of material on energy demand was omitted (the influence of thermal transmittance was ignored), and the only factor was the temperature in the print head.

Discussion and conclusions

The conducted measurements showed an increase in energy demand of the printer head depending on both temperature of the head and temperature in the printer chamber. In case of ATMAT Signal printer and a nozzle with a diameter of 0.8 mm, the average increase in energy demand with an extrusion temperature increase of 20°C was 13%, and in case of new solution and a 2.5 mm nozzle it was 20%, but these values should not be combined due to different measuring points and also because this increase is not linear - a greater change in demand occurs at higher absolute temperature values, especially in the case of new technologies developed for bigger workspaces in this project, where when changing the temperature of the head from 280°C to 300°C, the increase in energy demand reaches even 28.1%.

The temperature change in the working chamber from 40°C to 30°C showed an increase in energy demand by an average of 6.9% for ATMAT Signal printer and 4.8% for research subject. However, the simple dependencies between the influence of the table temperature and the increase in energy demand were not shown (only a significantly smaller dispersion of the increase in new print head and algorithms design ($\sigma = 2.5\%$) compared to the ATMAT Signal ($\sigma = 4.7\%$) was revealed), the determination of this impact is planned in correlation with developing stage of research, where it is planned to measure a much larger number of printer parameters.

In FDM type printers, regardless of their size, there is a large number of variable parameters that affect temperature regulation in the head, this temperature has a key impact on the quality of the printed model. It was found that, in addition to the expected temperature in the head (set value), the regulation is also influenced by other parameters (e.g. temperature in the printer chamber), hence the conclusion that it is justified to prepare an improved algorithm for regulating temperatures in the printer - one that, contrary to the currently used solutions, will also take into account other relevant parameters.

Another conclusion drawn on the basis of this research is that the influence of parameters on the energy demand of the printer heater is not related in a simple way, but in a more complicated, non-linear way. In further stages of research projects which is focused on further development,
the research team carried out further studies on ways to integrate achieved results and the essence their impact in cooperation with the rest of printer construction. Simultaneously further analyzing other parameters on energy demand and quality of temperature regulation.

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