Process Based Modeling of Energy Consumption for Multi-material FDM 3D Printing

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Process based modeling of energy consumption for multi-material FDM 3D printing

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Abstract:

Fused deposition modeling (FDM) is one most cost-effective 3D printing technique for forming complex 3D components based on thermoplastic materials. The energy consumption analysis is one criterion to determine the capacity and sustainability of the FDM. In this paper, the energy consumption of a dual- extruder FDM is studied by differentiating the whole multi-material printing process into independent operation modes, which characterize the thermal behaviors of the printing parameters. By investigating the execution instruction which describe the tooling plan of the FDM, the nozzle temperature distributions with different filament materials are measured and simulated. The energy consumption details can be accurately captured in our work and therefore we are able to predicate the power demand changes with different working processes of the multi-material FDM 3D printing. This work will be

beneficial for optimization of 3D printer design and manufacturing sustainability in next.

Keywords : Fused Deposition Modeling; Process Parameters; Energy Analysis; Multi-Material 3D Printing.

1 Introduction

Fused deposition modeling (FDM) is widely considered as one most cost effective additive manufacturing (AM) technique for building a 3D complex structure by extruding the liquified thermoplastic or thermoset filaments through a small diameter nozzle [1], for which energy consumption analysis is one prerequisite to evaluate its printing capacity and manufacturing sustainability [2]. For a FDM printing process, Peng [3] proposed a two-level energy analysis method based on the energy flow during the printing process. The primary energy is the thermal energy required for melting the printing filaments, and the secondary energy is the auxiliary energy input to drive the mechanical movements, auxiliary temperature fields, etc. Ajay etc. [4] obtained the impacts of printing accuracy, printing speed, and temperature on the energy consumption and found that the heat energy consumption in the printing process accounts for about 40% of the total power consumption. Therefore, Le Bourhis etc. [5,6] analyzed each printing parameter comprehensively and established a prediction model on the power factor of the consumable filament material.

From 3 different FDM printers, Clemon etc. [7] found that most of the energy actually went to the heating elements during the printing. Therefore, Mongol etc. [8] began to explore the impact of other in-process printing parameters on energy consumption and noticed that the placement of parts would also impact the final printing power consumption. Balogun etc. [9] conducted a unified analysis of three different FDM printers, and summed up the power consumption characteristics of the main working stage of the printer. They found that the printer reduced the loss of thermal energy with continuous printing under a full task requirement [10,11]. Lately, when the effect of layer thickness and packing density on the mechanical properties of parts were studied [12], the researchers also found that, compared with traditional subtractive manufacturing, higher dimensional accuracy did not necessarily need higher power consumption. For a high-precision energy consumption prediction, Yosef etc. [14] recently divided the FDM printing process into different working stages, and obtained the energy consumption model for each stage through experiments. Therefore, Ajay etc. [15] analyzed the printer motion execution instructions, and proposed turning off the other axis drive motor to achieve energy saving in a single axial movement. As a result, energy was saved by 25% with new printing strategy.

The existing researches only focused on the FDM 3D printing of a single type of material and the temperature field during printing can be assumed as constant. However, FDM printer with multiple extruders have overwhelmed in both academic and industrial sectors [16], in that it can directly fabricate a complex functional 3D part [17]. The variety of materials in multi-material FDM 3D printing may own very different melting temperatures and as a result frequent power switching (on, off, increase, decrease) was required during the printing of a multi-material part [18,19]. These influences would cause the complexity with evaluating the electrical energy consumption. Therefore, this paper will draw on how to model the power necessary to drive a dual – extruder FDM 3D printer, which will help with optimizing multi-material FDM design and also other extensive types of AM.

Table 1. Properties of 3D printing materials

Materials	*ABS*	PLA
Nozzle temperature/°C	*230*	200
Build plate temperature/°C	*80*	60
Stand by temperature/°C	*200*	175
Fan speed/%	*5*	100
Print speed/mm $\cdot s^{-1}$	*40*	40

2 Experimental section

Shown in Error! Reference source not found. is our experimental setup for energy analysis, where a dual - extruder FDM 3D printer Ultimaker 3 (from Ultimaker Inc.) was utilized. Two different filament materials ABS and polylactic acid (PLA) were directly used with their properties as listed in **Error! Reference source not found.**, in which the "ABS" nozzle and "PLA" nozzle were defined for their corresponding material types, respectively. Three energy consumption modules were defined according to the FDM infrastructure, including (a). the motion module, which is related to the motion movements of three axes and extruder motor; (b). the heating module, consisted of two liquefier heaters and one building platform heater; (c). peripherical module (or constant power consumption mode), including LCD, cooling fan, and main control board, etc.

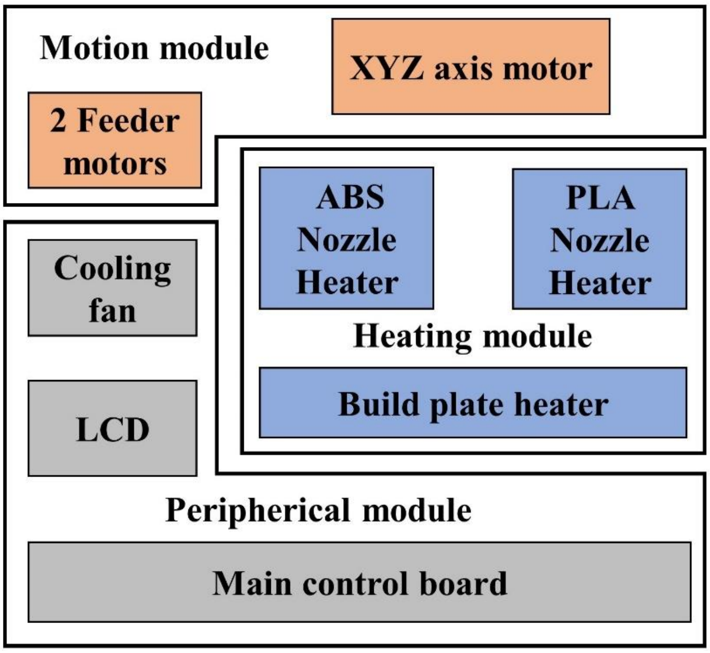

Figure 1. Hardware composition diagram of dual material FDM printer

The FDM 3D printer was hooked up to a DC (direct – current) driven constant voltage power supply (62015L, Chroma ATE Inc), which provided the access to measure the driving current and voltage. Shown in **Figure 2**, an oscilloscope DSO-X3024T (Keysight, Inc.) was used to measure the internal MOSFET operating frequency of 1kHz, and according to Nyquist Theorem the data acquisition sampling frequency should be set at 10kHz, about 10 times of the signal frequency [20,21]. Precision resistors were connected in series with the power supply of the FDM printer, and the voltages on the resistors were sampled by DAQ NI9205 (National Instruments, Inc.) to further calculate the currents as required for power evaluation. All the tests were carried out at room temperature.

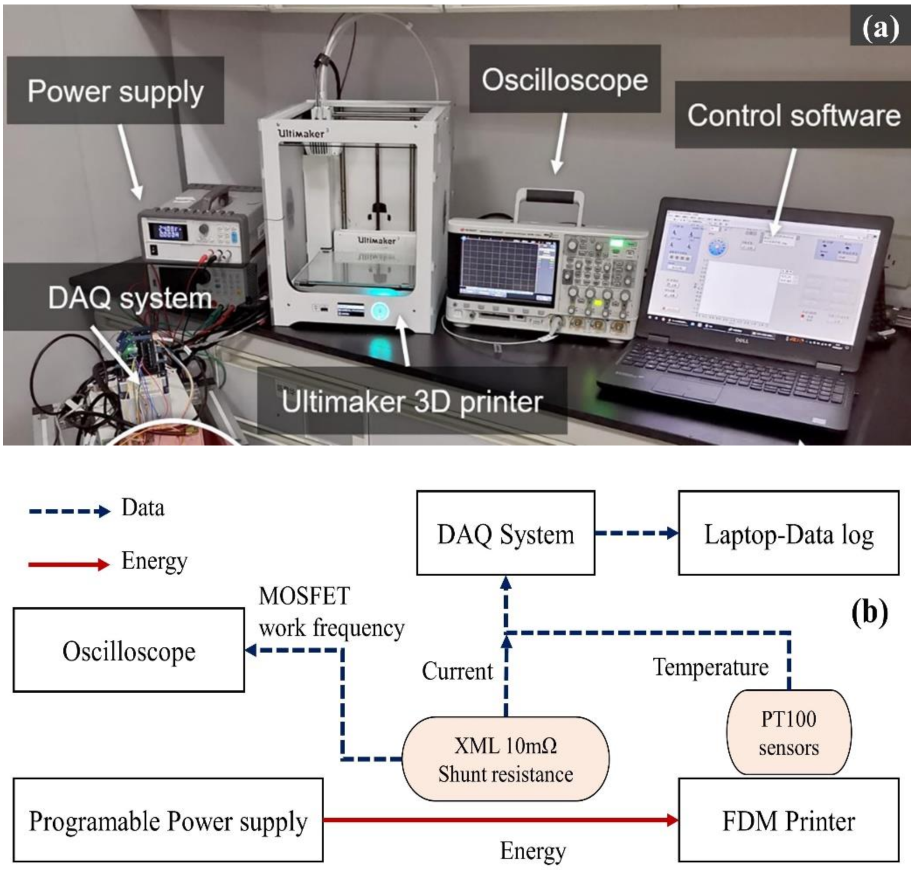

Figure 2. Experimental apparatus and block diagram(a) experimental setup for energy analysis;(b) test circuit diagram.

For multi-material FDM 3D printing, we designed a printable cylindrical "Yin" and "Yang" 3D part shown in **Figure 3** with the height 2.5mm and diameter set as 30mm, in Chinese philosophy which represents two principles: one negative, dark, and feminine (Yin); and one positive, bright, and masculine (yang). The part was first sliced into printing layers at a thickness of 0.2mm During printing of each layer, the ABS filament was first extruded out from "ABS" nozzle and deposited in the "Yin" zone, by ramping the nozzle temperature from 200 to 240 °C. For “Yang” zone, the PLA filaments were extruded out from “PLA” nozzle and deposited by heating temperature as maintained at 175°C. Recorded were the driving current and voltage datum to the computer in real-time during the printing process.

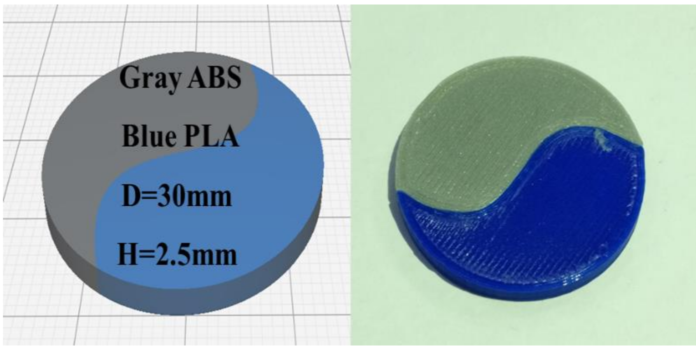

Figure 3. Printed models and physical objects composed of blue PLA and gray ABS

3 Results and discussion

The power consumption of the FDM printer at the idle mode was first calibrated by measuring the required minimum power to drive the peripherical module, such as the control motherboard, the LCD, and the cooling fan. The power at the idle mode was constant in this study. Secondly, preheating mode of FDM was switched on, in which the building plate was heated up to its pre-set value, and then the printing nozzle started to be heated for melting the filament. For the FDM 3D printer, its “ABS” nozzle was directly heated up to 240 °C, slightly higher than the melting temperature of ABS material. This nozzle temperature was maintained whenever the whole ABS material was printed. When the two materials ABS and PLA were printed, both “ABS” and “PLA” nozzles were heated to their own standby temperatures, i.e. 200°C for ABS and 175°C for PLA, respectively.

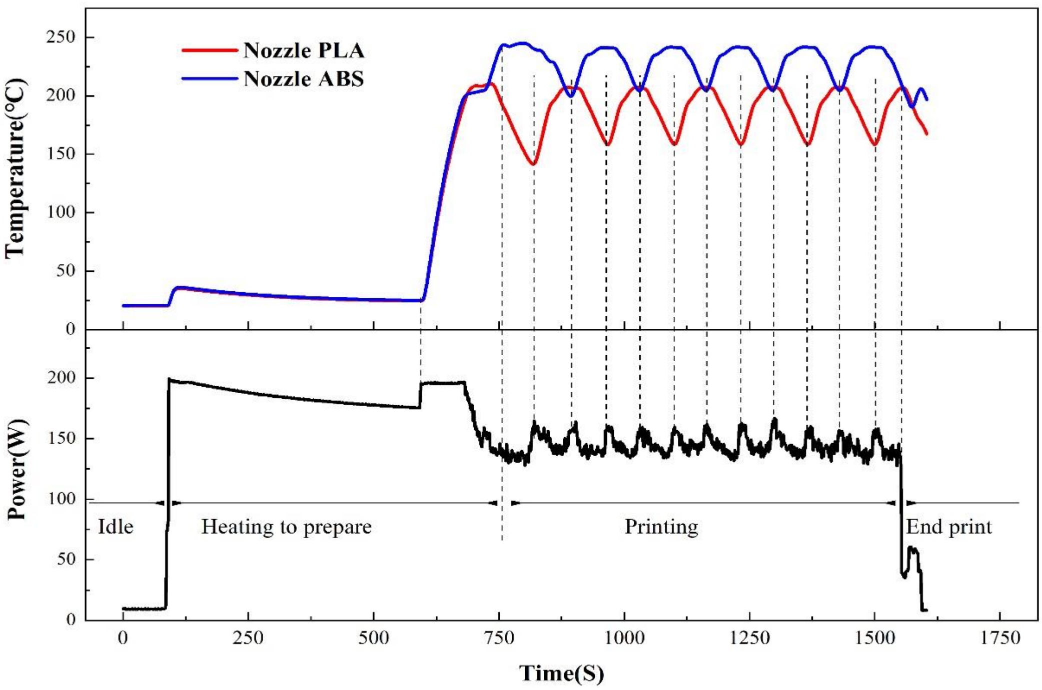

Figure 4.Printer nozzle temperature and power

As shown in **Figure 4**, when the printing material was switched from PLA to ABS, the printer did not completely switch off its input power and instead somehow adjusted it for maintaining the nozzle temperature just slightly below the melting temperature of ABS. This process last until the next printing cycle. At the same time, the printer started to turn up the electrical power for melting PLA along its own heating curve. These heating curves can be determined through measuring the heating capacities of ABS and PLA materials. It was noted that, in the printing, the temperatures of the two printing nozzles were frequently adjusted and therefore the power was fluctuating as shown in **Figure 5**.

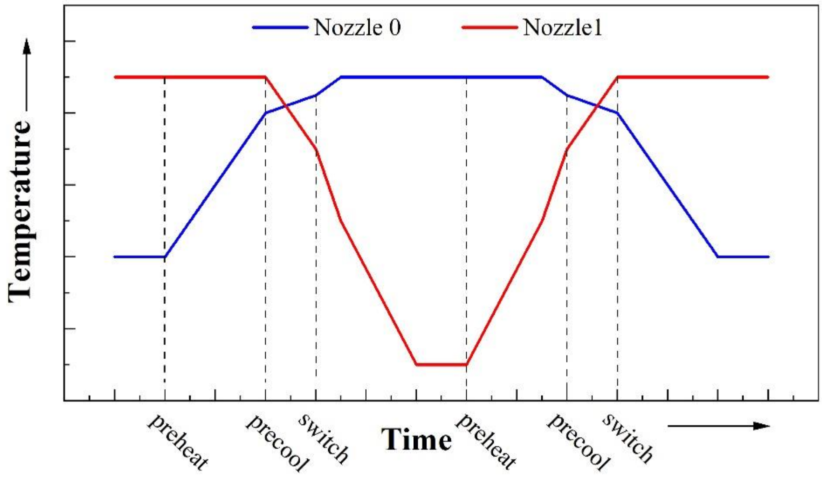

Figure 5. FDM Printer Dual-nozzle switching process

Once finishing with the 3D printing, the FDM printer would enter into an end mode, where the printer maintained both nozzles at a relatively high temperature for a while and prevented the overcharged printing materials from clogging the nozzle. Therefore, according to Ref [14], the overall power consumption P_{total} of the system can be calculated by

$$P_{total} = P_{idle} + P_{build\,plate} + P_{abs\,nozzle} + P_{pla\,nozzle} + P_{motors} + P_{extruders} \#(1)$$

where P_{idle} is the power consumption at idle mode; $P_{build\,plate}$ is the required power to heat the build plate; $P_{abs\,nozzle}$ and $P_{pla\,nozzle}$ represent the electrical power added on the "ABS" nozzle and "PLA" nozzle; P_{motors} is the power to drive three-axis movements of the FDM 3D printer; and $P_{extruders}$ are the power used to drive the extruder motors to fuel the filaments into the heating nozzle. Table 2 gives the required power for each printing parameter as well as the related Gcode execution instruction. For example, when a nozzle was set to maintain at 220°C for preheating the ABS, an electrical power input of 24W was in need. And this calibration was done by us to run the Gcode command of "M109 S220".

Table 2.The power consumption of the tested instruction

Parameter or state	Gcode instruct	Power(W)
Idle	\	9
Build plate warm up	\	144
Build plate maintain 80℃	\	72
Single nozzle warm up	M109 S M104 S	24
Nozzle maintain 220℃	M109 S220	24
XYZ axis motion and feeder motion	G1F1200 X()Y()Z()E()	24

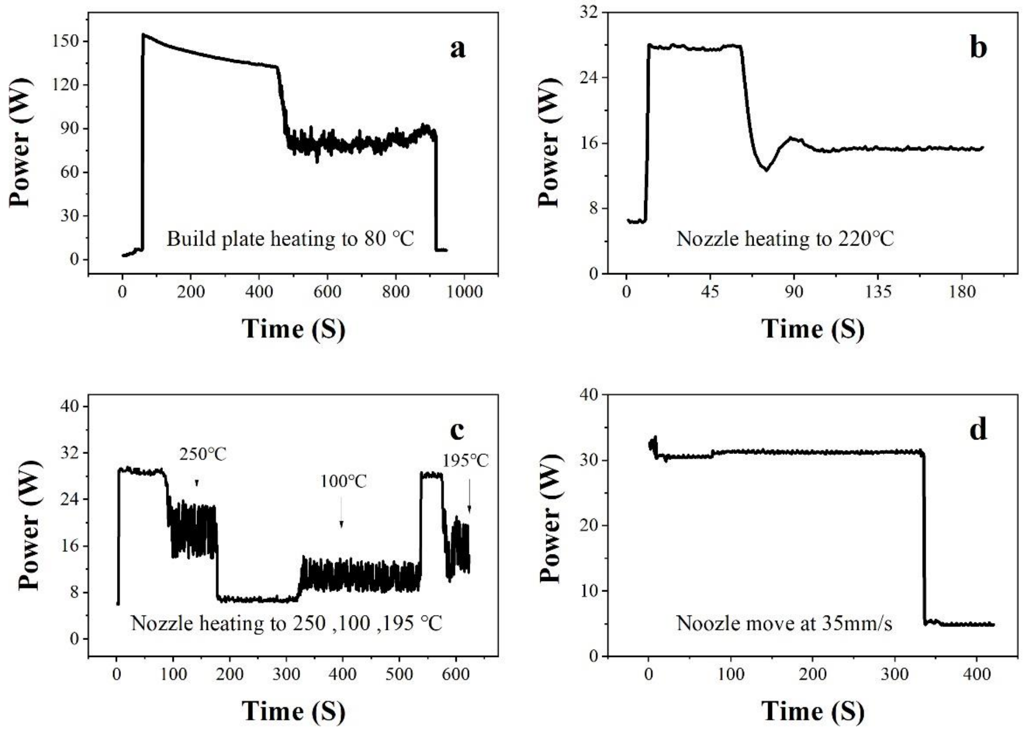

Figure 6. Printer nozzle and build plate power under the specified temperature (a)power of build plate heating to 80℃;(b)power of nozzle heating to 220℃;(c)power of nozzle heating to 250℃ then cool down to 100℃ then heating to 195℃;(d)the power of nozzle move at 35mm/s without heating.

Once Table 2 and other possible printing parameters under investigation were obtained, **Figure 6a** demonstrated the power curve for the build plate heated from room temperature to 80° C by running the Gcode. There, the maximum power for heating the build plate was 144w, which determined the higher mean power at the preheating stage. The power of the building plate still occupied more than 50% of the total power as consumed during the whole printing. The heating power consumption of the nozzle was then recorded by ramping the temperature from the room environment to 220°C, as shown in **Figure 6b**. A simple control strategy was deployed for this FDM 3D printer, in **Figure 6c**, such as: when the temperature was raised, it was heated at a full power input; and when the temperature was lowered down, the heating power was completely turned off until the preset temperature was reached, and then it was turned to a low-power mode holding constant temperature. In final, the power consumption of the motion motor module was shown in **Figure 6d**.

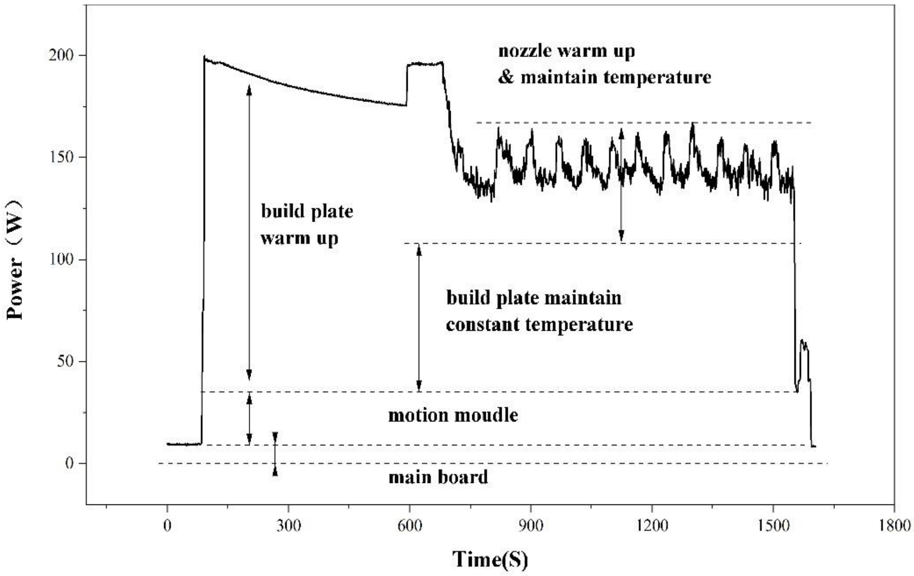

Figure 7. FDM printer consumption power composition

For summary, the power input curve for a full cycle of 3D printing was demonstrated in **Figure 7**, where the power curves for all of operating modes in 3D printing can be identified and actually calculated by directly extracting the relevant commands in the Gcode file, shown in Table 3.

Table 3.Detailed information by parsing Gcodes

Gcode	Behavior description
M109 S205	Heat the nozzle until the temperature reaches $205℃$
G0 F15000 X9 Y6 Z2	Nozzle moves to X9, Y6, Z2 coordinate points at a speed of 15000mm/min
G280	Movement axis returns to origin
G1 F1500 E-6.5	Extruder draws back $6.5mm$ material at print speed of 1500mm/min

M204 S625	Maximum accelerator $a_{max} = 625mm/\text{s}^2$
M205 X6 Y6	XY axis maximum jerk $j_{max} = 6mm/s^3$
G0 F4285.7 X95.983 Y94.978 Z0.27	Printing nozzle moved at a speed of $F = 4285.7\,mm/min$ to arrive at $\text{X67.619, Y104.127, Z0.27}$
M204 S500	Maximum accelerator $a_{max} = 500mm/\text{s}^2$
M205 X5 Y5	XY axis maximum jerk $j_{max} = 5mm/s^3$
G1 F1500 E0	Extrude material to $0mm$ at a print speed of $1500mm/min$
G1 F1200 X96.89 Y94.159 E0.02172	Printing nozzle moved at a speed of $F = 1200\,mm/min$ to arrive at X696.89Y94.159, extrude material to $0.02172mm$

We had the initial velocity $U_{initial} = 1500\,mm/min$, printing nozzle moved from the position of (X9,Y6) at a moving speed of $F = 5000\,mm/min$ to arrive at X67.619,Y104.127, in which the maximum accelerator $a_{max} = 625\text{mm}/\text{s}^2$ and the maximum jerk j_{max} is $6\text{mm}/s^3$. And the moving speed was set as $V_{\text{set}} = 5000/60 = 83.3mm/s$. The required distance to approach maximum speed can be calculated by:

$$S_i = \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2}\#(2)$$

$$v_a = \frac{{a_{\max}}^2}{j_{\max}}\#(3)$$

$$s_a = \frac{2 \cdot {a_{\max}}^3}{{j_{\max}}^2} \#(4)$$

$$t_j = \sqrt[3]{\frac{S_i}{2 \cdot j_{max}}} \#(5)$$

Since the overall movement distance of the printer is limited, the movement of G1 was assumed to be variable acceleration. Therefore, the time for taking the printer to execute this instruction T_{move} was:

$$T_{move} = 4 \times t_j = 4 \times \sqrt[3]{\frac{S_i}{2 \cdot j_{\max}}} \#(6)$$

For the command of G1, the running duration was：

$$T_i = \frac{S_i}{F_i} \#(7)$$

where S_i was the distance of each segment, and F_i was the speed.

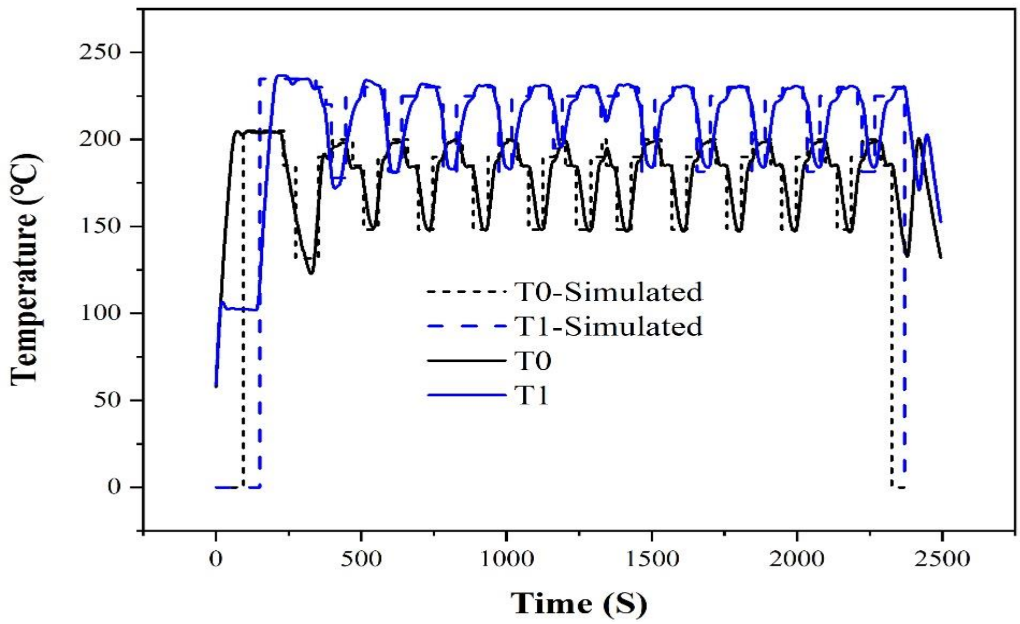

Figure 8. The predicted temperature curve is compared with the actual temperature

Based on Equation (6) and (7), we can get the estimation on the temperature and the time for the printing process operation modes in FDM, shown in

Figure 8. The power and time diagram can be drawn based on the measured

temperature and power curves. The whole analysis of the power consumption of the FDM was following the flowchart shown in **Figure 9**.

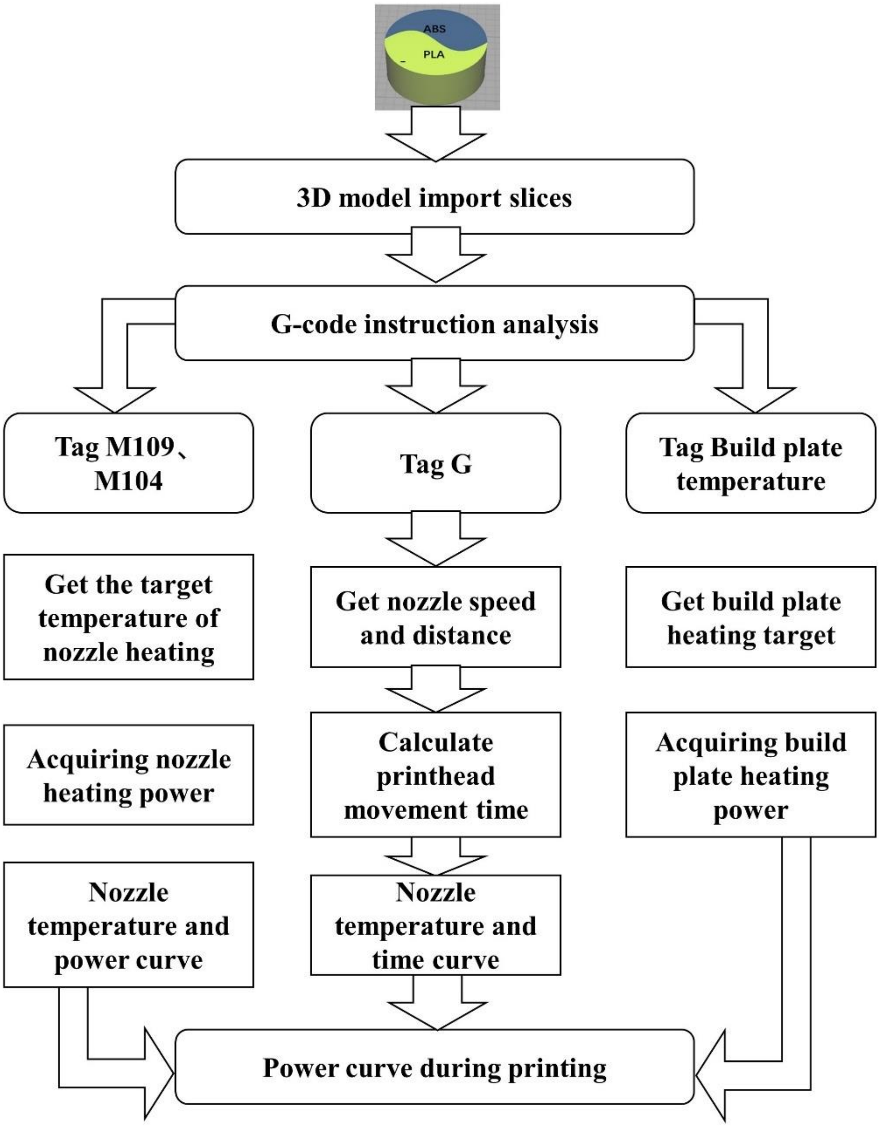

Figure 9. Analysis flow from gcode instruction to power graph

The overall trend based on theoretical estimation performed in consistance with the experimental measurements as shown in **Figure 10**. There was a small margin of error in time synchronization for estimation. The small difference might lie in that: first, the operating environment, including room temperature and cooling fan installation, could cause less control on the air convection and therefore the heating efficiency; secondly, the heating efficiencies of the two nozzles somehow distinguished from each other. In **Figure 10**, although there is a certain deviation between the predicted value and the actual value, the predicted power map fully reflects the fluctuation amplitude and time range of the power change during the bi-material printing process.

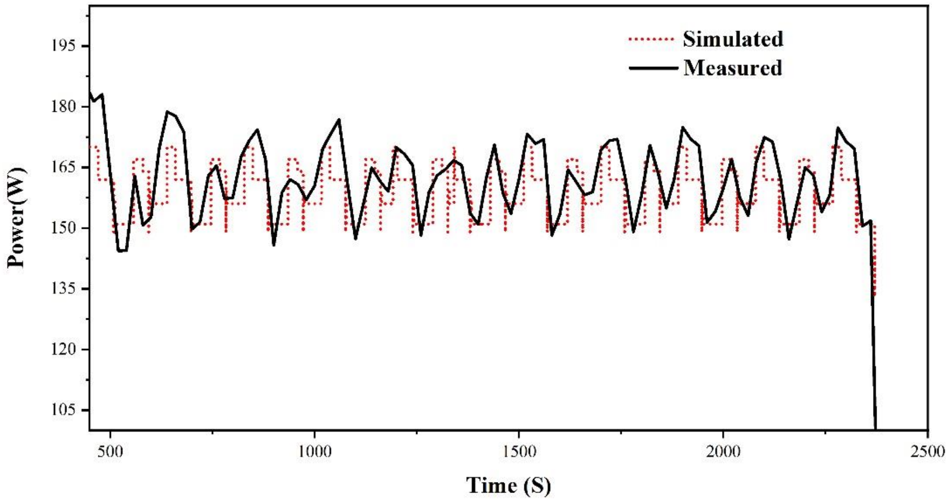

Figure 10. Comparison of estimated power with actual power

4 Conclusion

This paper combines the analysis of unit energy consumption with the analysis of FDM printer instructions, through system parameter calibration and G-code analysis, proposes a method for predicting the change in power demand during multi-material FDM printing. Will help improve the reliability of FDM printer operation in energy-stressed environments. Currently, this method relies on the prediction of temperature, so the environment has a greater impact on the accuracy of the prediction.

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Authors' contributions

YL and JHC analyzed and interpreted the experimental data regarding energy consumption of the FDM; YL, JHC and YQC designed and performed the experiments; JHC and EWS programmed the software for data collection; YL and JHC wrote the manuscript. All authors read and approved the final manuscript.

Availability of Data and Materials

The data during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing financial interests.

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Figures

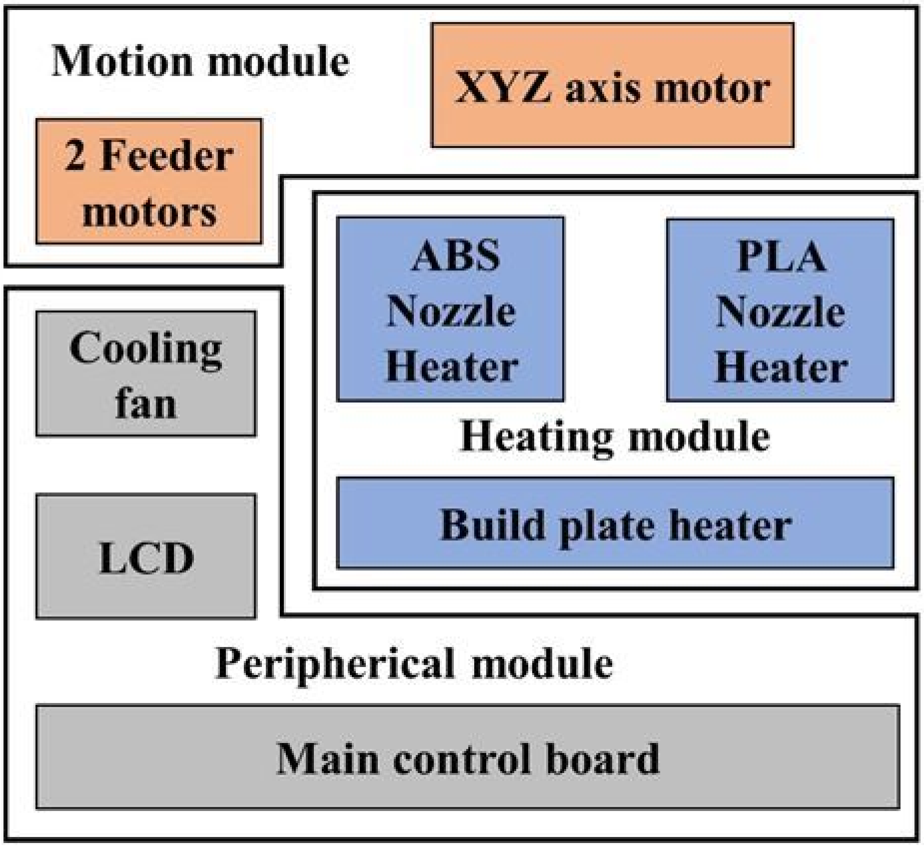

Figure 1

Hardware composition diagram of dual material FDM printer

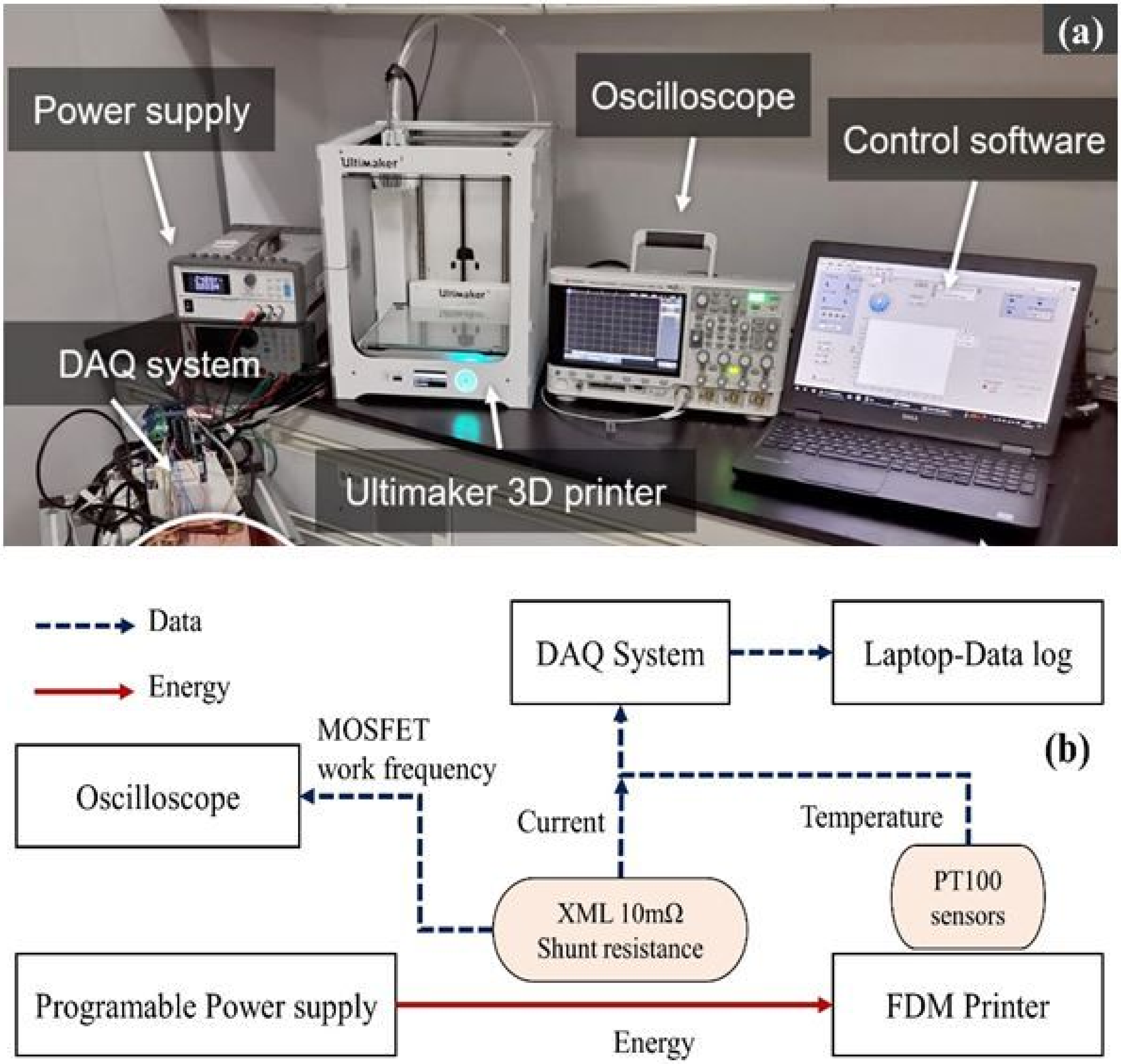

Figure 2

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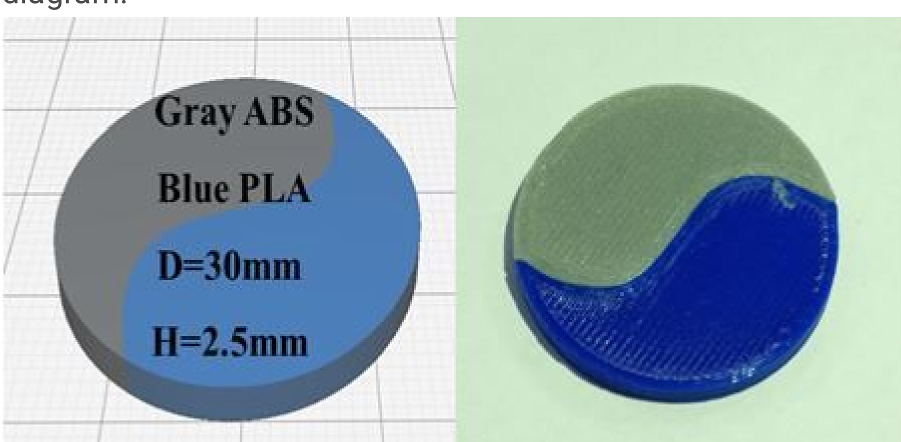


Figure 3

Printed models and physical objects composed of blue PLA and gray ABS

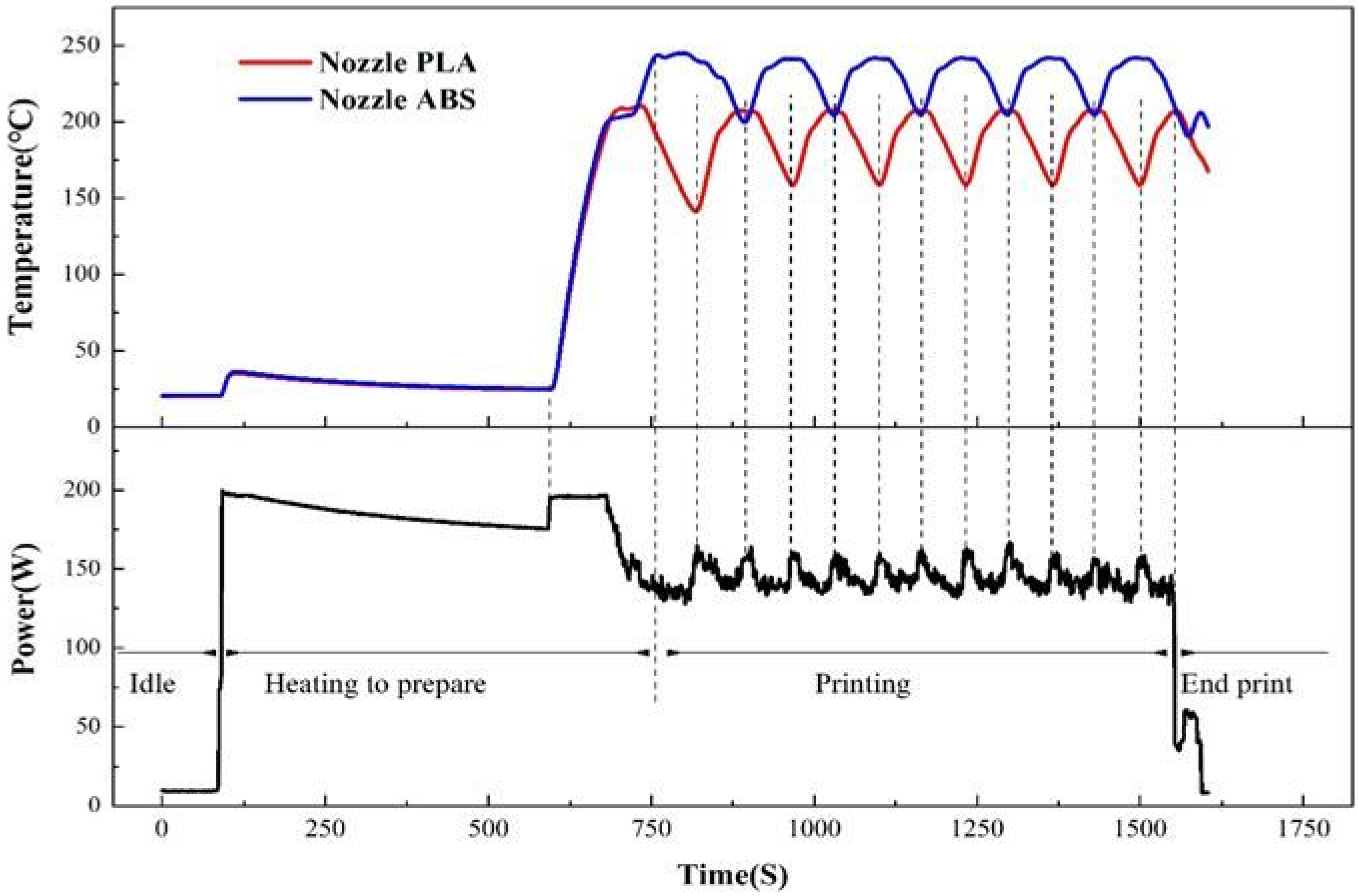


Figure 4

Printer nozzle temperature and power

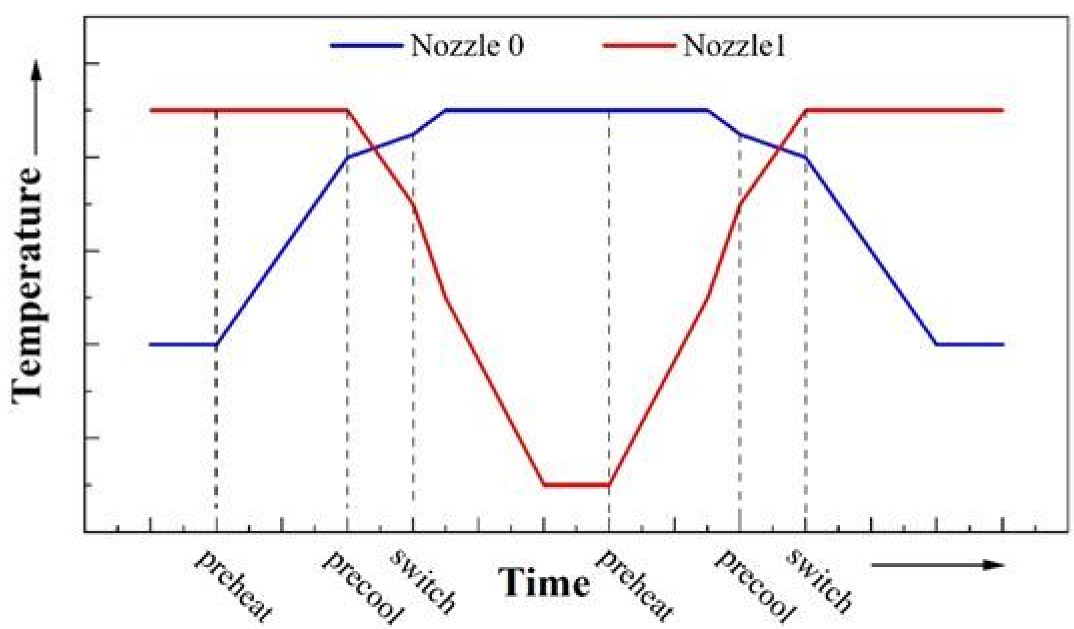


Figure 5

FDM Printer Dual-nozzle switching process

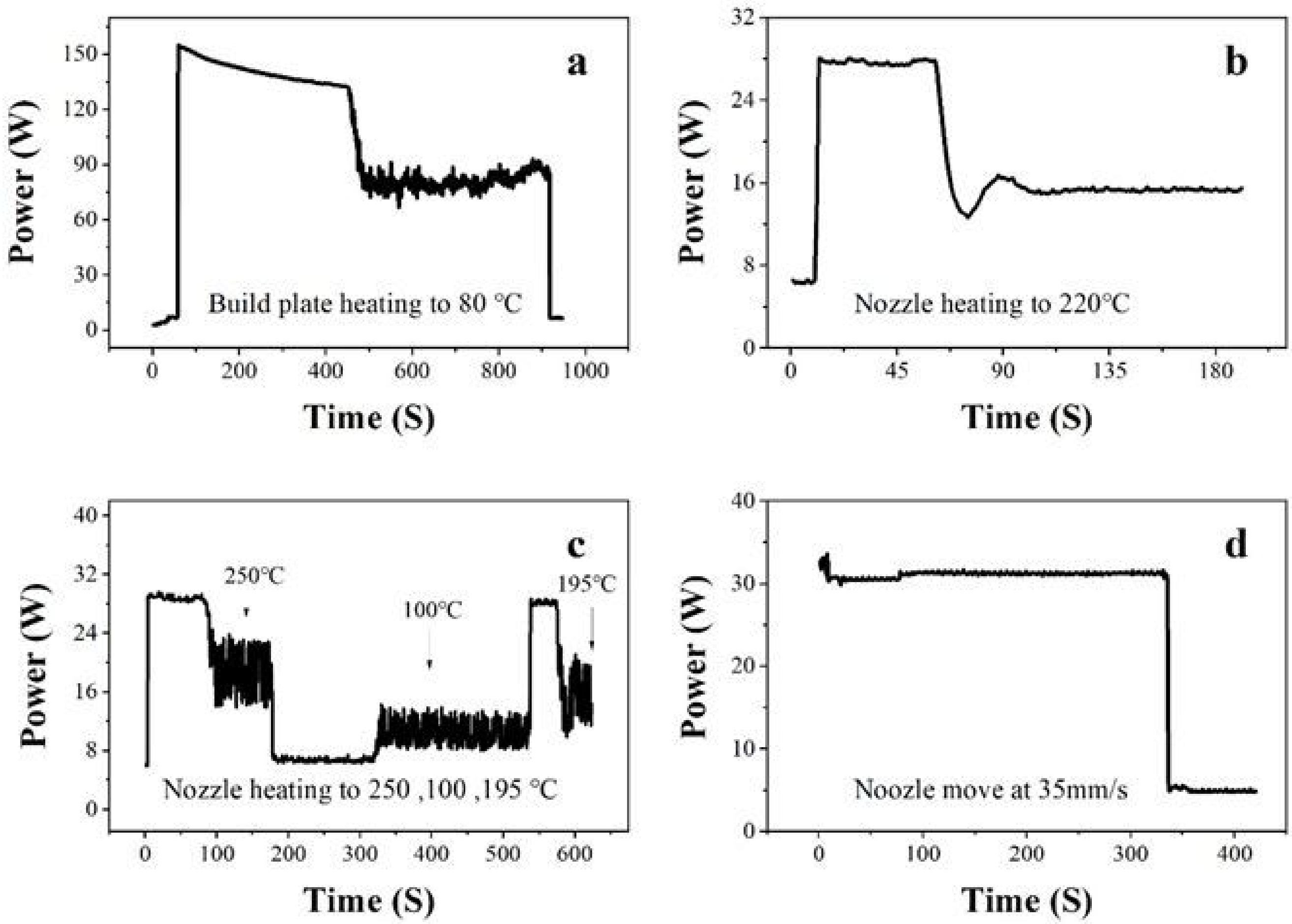


Figure 6

Printer nozzle and build plate power under the specified temperature (a)power of build plate heating to 80℃;(b)power of nozzle heating to 220℃;(c)power of nozzle heating to 250℃ then cool down to 100℃ then heating to 195℃;(d)the power of nozzle move at 35mm/s without heating.

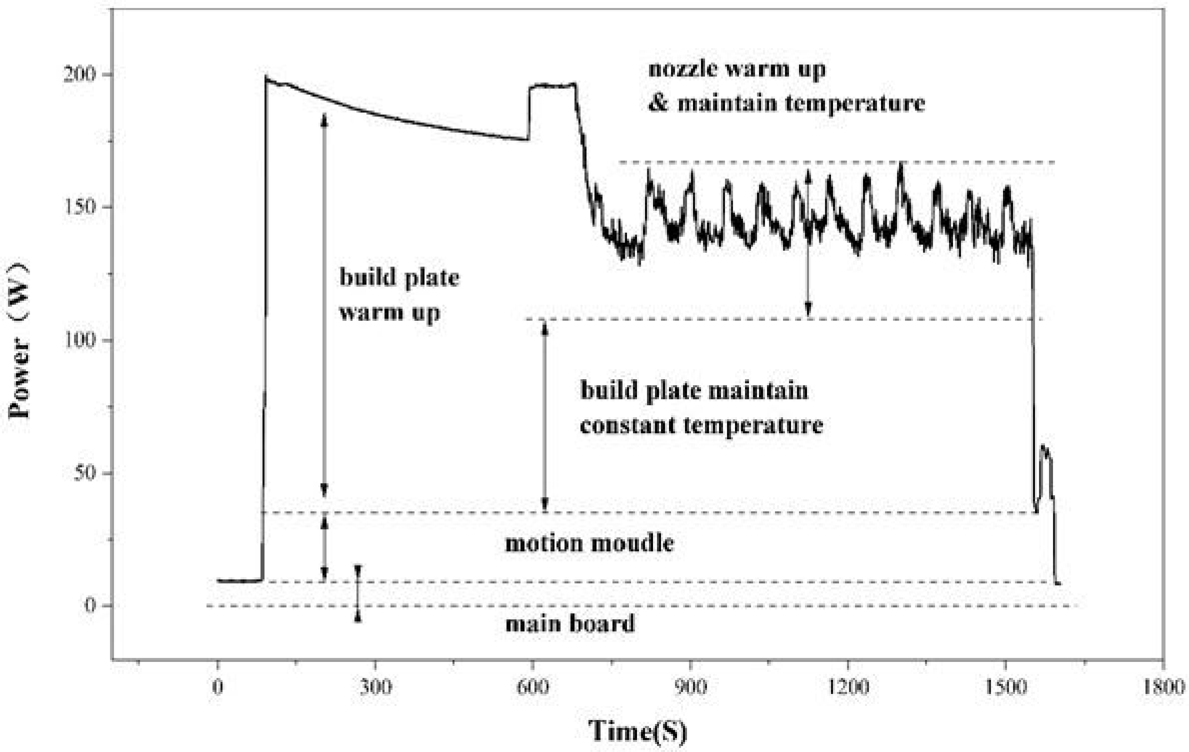


Figure 7

FDM printer consumption power composition

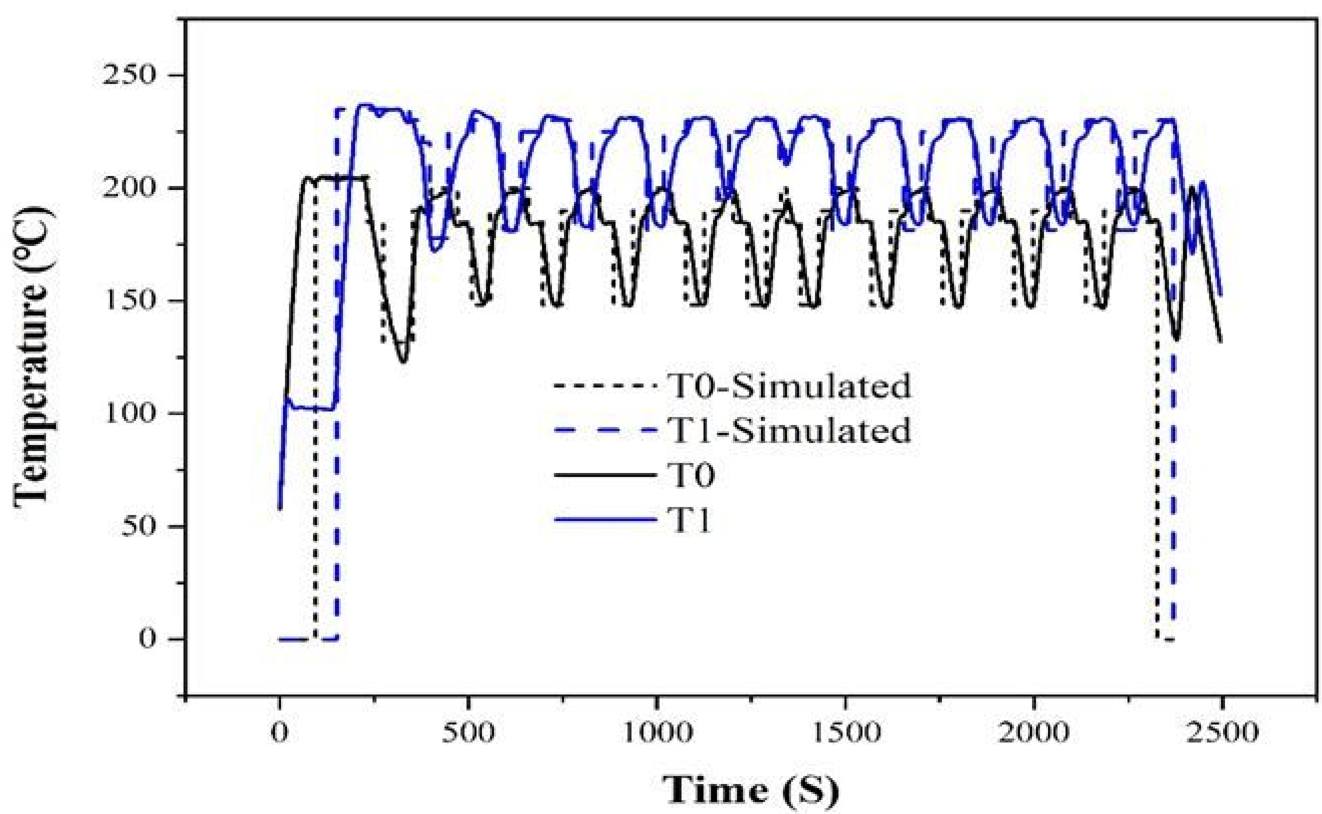
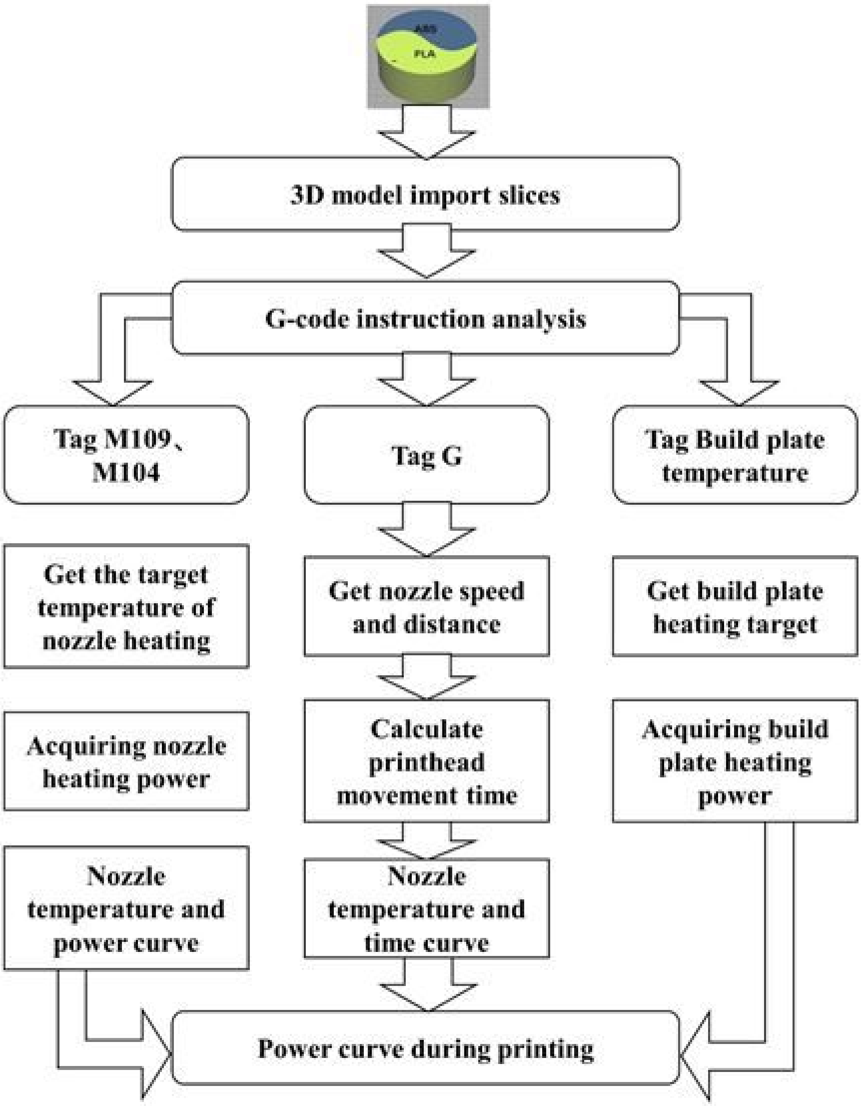


Figure 8

The predicted temperature curve is compared with the actual temperature



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Analysis flow from gcode instruction to power graph

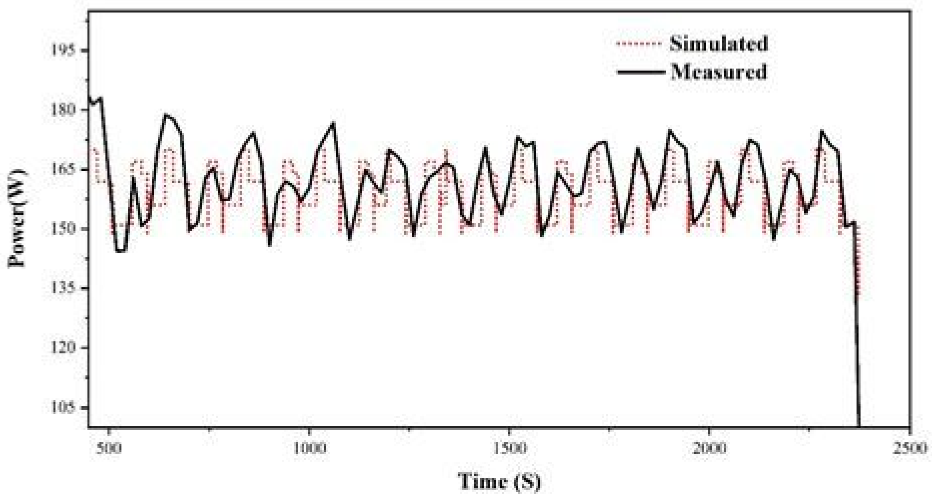

Figure 10

Comparison of estimated power with actual power