Mosquito Magnum+ 1.75 Maximum Practical Flow Rate Test

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Abstract— **Volumetric flow rate in Fused Filament Fabrication (FFF) is a measure of the amount of plastic a hotend can extrude in a given time period. Mosquito Magnum+ is the newest hotend introduced by Slice Engineering with the goal of providing users an option for substantially increased flow rates and, therefore, improved print speeds and reduced print times. Practical average maximum volumetric flow rates for Mosquito Magnum+, installed on a specified printer, were identified for several materials to give users a better understanding of the maximum print speeds achievable without compromising print quality. To measure the average maximum volumetric flow rate possible from the target hotend, a series of test prints were conducted at various speeds with Ø1.75 mm filaments of different materials. All tests used a narrow but long 20 mm tall object that was easy to observe during printing with specific geometry designed to illustrate interlayer adhesion. During each test, print speeds were increased gradually in a controlled way, starting with the slowest speed at the bottom and increasing the speed by a set amount at specific print heights. Each test print was then visually inspected for defects. The maximum average volumetric flow rate achieved by Mosquito Magnum+ was 53 mm³/s when printing acrylonitrile butadiene styrene (ABS) at a temperature of 240 °C and 91 mm³/s at a temperature of 300 °C. The maximum average volumetric flow rate achieved by Mosquito Magnum+ was 65 mm³/s when printing polylactic acid (PLA) at a temperature of 220 °C and 88 mm³/s when printing at a temperature of 280 °C. The maximum average volumetric flow rate achieved by Mosquito Magnum+ was 71 mm³/s when printing high impact polystyrene (HIPS) at a temperature of 245 °C and 93 mm³/s at a temperature of 305 °C. Each test print had acceptable interlayer bonding adhesion at least up to the point of failure.**

Index Terms— **Mosquito Magnum+, Hotend, Volumetric Flow Rate, Print Speed, Fused Filament Fabrication, more commonly known as Fused Deposition Modeling, Slice Engineering.**

I. Introduction

THE increased need for larger build volumes and higher production outputs has exposed a particular weakness in the technology of filament fused fabrication (FFF), namely print speeds. Print speed is a significant obstacle in the further development and implementation of FFF in both small and large-scale production because of its implication for production costs versus a traditional manufacturing method such as injection molding, which can be many times quicker on a per unit scale. Slice Engineering had a goal of providing its customers with a product that would allow for increased print speeds to help mitigate the gap between traditional manufacturing and FFF additive manufacturing. To do this, Slice focused on hotend performance. The hotend is the part of an FFF 3D printer that liquifies a rigid polymer filament and deposits it onto the build surface. The result of this work was Mosquito Magnum+, a new hotend product that provides higher volumetric flow rates and that can be integrated into a machine as an upgrade or added as an option to a new printer purchased through an OEM.

Volumetric flow rate in FFF is a measure of the amount of plastic a hot end can extrude in a given time period. The maximum print speed achievable in FFF is related to the maximum volumetric flow rate that the hotend can deliver. However, there is no agreed upon standard for carefully measuring maximum volumetric flow rate limits in FFF. In the absence of an agreed upon method or standard, it was determined that measurements would be made based on printing a specific object with a calculated volume and determining flow rates based on the print times. This method has the significant advantage of being both easy to understand and easy to replicate.

The primary goal was to establish the maximum volumetric flow rates of Mosquito Magnum+ on a specified printer to give users a better understanding of the maximum print speeds achievable without compromising print quality. Three different materials were chosen for testing, each for a specific reason. Polylactic acid (PLA) was chosen because it is one of the most commonly used materials in FFF 3D printing. Acrylonitrile butadiene styrene (ABS) was chosen because of its prevalence in many different industries including aerospace and automotive. Finally, high impact polystyrene (HIPS) was chosen because it is often used as a support material for more complex geometries.

II. Procedure

A. Test Method

To measure the maximum volumetric flow rate possible from the target hotend, a series of test prints were conducted at various speeds with Ø1.75 mm filaments of different materials. All tests used a 20 mm tall object with specific geometry designed to illustrate issues with interlayer adhesion. Poor interlayer adhesion is a common result of printing too quickly. When polymer is pushed through a hotend too quickly, a temperature differential can be created, causing the surface of the filament to be a significantly greater temperature than the center. This can be referred to as the cool center effect. The cool center effect is known to cause bonding issues between each printed layer. This results in an overall weaker part. During each test, print speeds were increased gradually, starting with the slowest speed at the bottom and increasing the speed by a set amount at specific print heights. Each test print was then visually inspected for defects. For the first test of each material, an initial print speed was selected based on the primary researcher's experience with that material. Initial print speeds for subsequent test prints were varied based on the outcome of the initial test and each subsequent test.

The print tests were created and sliced using Simplify3D slicer software and saved as factory files, each corresponding to a certain material and print temperature. Within each factory file, it is possible to create multiple processes with slightly different print settings and then group and print these processes continuously in a single test print. As mentioned before, print speeds were increased gradually during a single print. This was done by setting the first process in a test print at the slowest speed, then increasing the speed by a set interval with every process change. Process changes occurred at every 5 mm height interval within the 20 mm tall test geometry, therefore, every Simplify3D factory file contains a group of four different processes. These were generated from a single process using Simplify3D's variable settings wizard. The Processes differ only by the print speed at each start-stop height. Process print speeds and start and stop heights are indicated in Table I.

The print temperatures were chosen based on the manufacturers' recommended printing temperatures and the manufacturer's recommended printing temperatures plus 60 °C. For each material, the higher print temperature was used to illustrate that a simple boost in temperature can be practical and effective when a boost in volumetric flow rate is needed. Steps 1 through 4 were followed to achieve the test results.

TABLE I
PRINT SPEEDS AND START-STOP HEIGHTS

Process	Programmed Print Speed (mm/s)	Start-Stop Heights (mm)
MaxFlow10-1	***B***	0 – 5
MaxFlow10-2	***B+5***	5 – 10
MaxFlow10-3	***B+10***	10 – 15
MaxFlow10-4	***B+15***	15 – 20

1. Process Group **Magnum+ MaxFlow10 *Material Print Temperature*** was printed to find a baseline programmed speed ***B*** that initiates flow-rate-driven abnormalities (e.g. gaps in the object, extrusion motor skipping steps, severely diminished precision) approximately mid-height (~10 mm).
   a. Iteratively increasing or decreasing baseline speed by increments of 5 mm/s gives sufficient resolution to discover a reasonably accurate value for ***B***.
   b. Repeatability was confirmed by printing the Process Group twice using the same ***B*** value.
2. The measured filament diameter d and length l in millimeters and print time t in seconds was measured and used to print the Process Group with the value ***B*** found in step 1. Print time starts recording after the purge line or at the start of the skirt/brim.
3. The average volumetric flow rate for the tested equipment and print settings is equal to the flow rate Q for the Process group printed.

$$Q = \frac{\pi d^2 l}{4t}$$

4. The term <u>maximum</u> average volumetric flow rate is applied to test outcomes where defects exist but only in the last two processes of the test print.

B. Equipment

The equipment used in testing was chosen specifically so that the hot end was most likely to be the limiting factor.

TABLE II
EQUIPMENT USED FOR TESTING

3D Printer	RailCore II 300ZL
Hotend	Mosquito Magnum+
Extruder	Bondtech QR Extruder 1.8° NEMA 17 Stepper
Nozzles	Ø1.0 orifice – Brass Bifurcated
Filament	Ø1.75 mm Printed Solid Jessie PLA Beige Ø1.75 mm 3DXTech 3DXMax HIPS Graphite Ø1.75 mm 3DXTech ABS Black
Filament Dryer	Purpose AMS FD5
Ambient Temperature	22 °C
Object	Zigzag thermal camera.3mf
Slicer	Simplify3D v4.0.1
Slicer File	**Magnum+ MaxFlow10 *Material Print Temperature*** Magnum+ MaxFlow10 PLA 220C.factory Magnum+ MaxFlow10 PLA 280C.factory Magnum+ MaxFlow10 HIPS 245C.factory Magnum+ MaxFlow10 HIPS 305C.factory Magnum+ MaxFlow10 ABS 240C.factory Magnum+ MaxFlow10 ABS 300C.factory

C. Print Settings

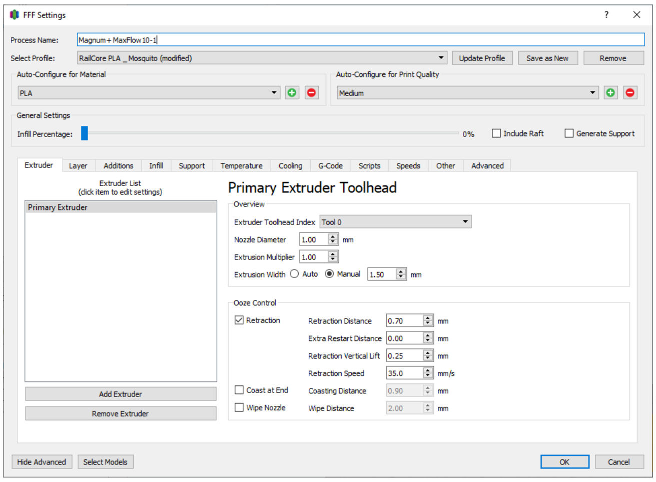

Fig. 1. Extruder Settings

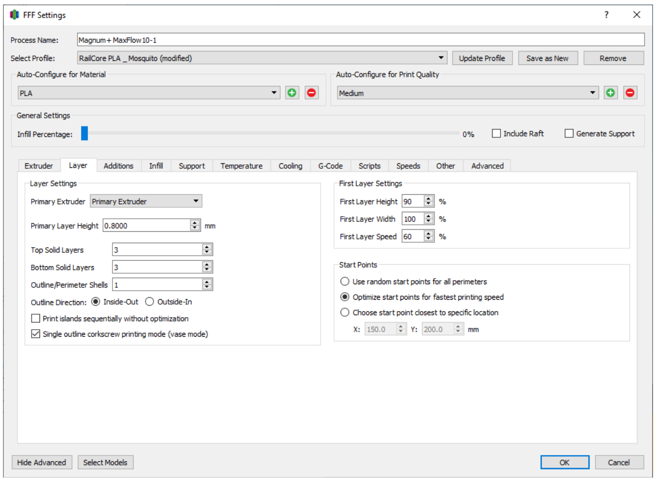

Fig. 2. Layer Settings

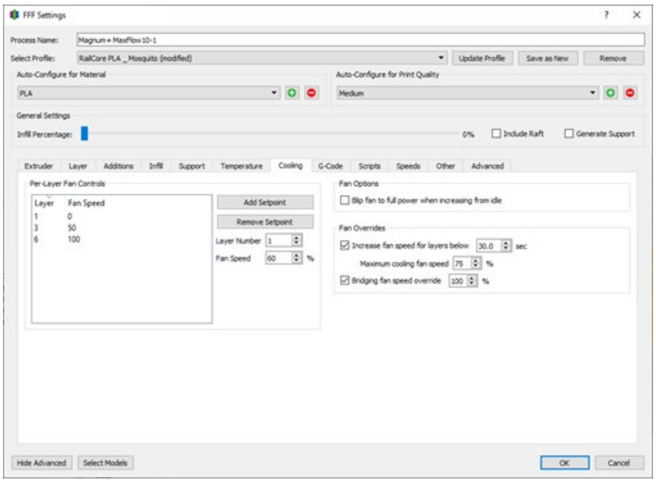

Fig. 3. Cooling Settings

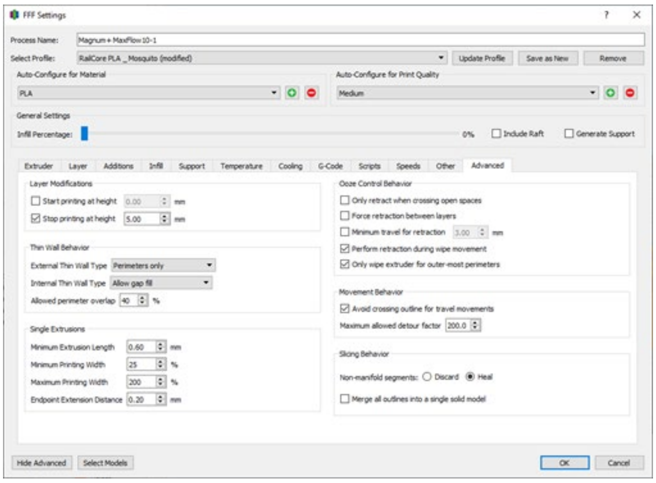

Fig. 4. Advanced Settings

III. Results

The maximum volumetric flow rate achieved by Mosquito Magnum+ was 53 mm^3/s when printing ABS at a temperature of 240 °C and 91 mm^3/s at a temperature of 300 °C. The maximum volumetric flow rate achieved by Mosquito Magnum+ was 65 mm^3/s when printing PLA at a temperature of 220 °C and 88 mm^3/s when printing at a temperature of 280 °C. The maximum volumetric flow rate achieved by Mosquito Magnum+ was 71 mm^3/s when printing HIPS at a temperature of 245 °C and 93 mm^3/s at a temperature of 305 °C. Each finding is detailed below in Table III. Following Table III is a description of each flow rate test and accompanying figure to show the test print and its failure point.

Table III
Practical Maximum Average Volumetric Flow Rate Measurements

Material	Mfr. Rec Temp (°C)	Baseline Print Speed ***B*** (mm/s)	Print Time *t* (s)	Slicer-calculated filament length *l* (mm)	Max Flow Rate (*Q*) in mm^3/s
ABS	240	40	850	18,973	53
	300	72.5	501	18,973	91
PLA	220	50	694	18,973	65
	280	70	520	18,973	88
HIPS	245	55	642	18,973	71
	305	75	490	18,973	93

A. *Mosquito Magnum+ ABS 240 °C*

A baseline programmed print speed B of 40 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 850 s yielded a flow rate Q of 53 mm^3/s.

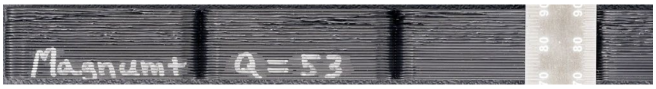

Fig. 5. ABS at 240C

B. *Mosquito Magnum+ ABS 300 °C*

A baseline programmed print speed B of 72.5 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 501 s yielded a flow rate Q of 91 mm^3/s.

Fig. 6. ABS at 300°C

C. *Mosquito Magnum+ PLA 220 °C*

A baseline programmed print speed B of 50 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 694 s yielded a flow rate Q of 65 mm^3/s.

Fig. 7. PLA at 220°C

D. *Mosquito Magnum+ PLA 280 °C*

A baseline programmed print speed B of 70 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 520 s yielded a flow rate Q of 88 mm^3/s.

Fig. 8. PLA at 280°C

E. Mosquito Magnum+ HIPS 245 °C

A baseline programmed print speed B of 55 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 642 s yielded a flow rate Q of 71 mm^3/s.

Fig. 9. HIPS at 245°C

F. Mosquito Magnum+ HIPS 305 °C

A baseline programmed print speed B of 75 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 18,973 mm, and print time t of 490 s yielded a flow rate Q of 93 mm^3/s.

Fig. 10. HIPS at 305°C

IV. Discussion

A. Summary

Slice Engineering decided there was a need to provide users with a more specific metric on a key hotend capability related to volumetric flow rate. Higher print speeds, and thus higher volumetric flow rates, are generally more desirable in 3D printing and Slice was looking for a way to showcase the capability of their new hotend. The research completed was designed to demonstrate both the suitability of the targeted test method and to identify practical maximum volumetric flow rates for a given hotend and material. A summary of results is provided in Table IV below.

Table IV
Summary of Flow Rate Measurements

Material	Mfr. Rec Temp (°C)	Max Flow Rate (Q) in mm^3/s
ABS	240	53
	300	91
PLA	220	65
	280	88
HIPS	245	71
	305	93

B. Procedural Comments

A key assumption for this study is the volume of the test print. The filament length calculated in Simplify3D (18,973 mm) is a theoretical length. No attempt was made to empirically establish the degree to which any test print achieved this length. Using the calculated filament length from a slicer is a typical practice in FFF to estimate price per part, weight of part, and the remaining filament for more prints.

Also, from a procedural standpoint, Slice was aware that higher printing temperatures can result in higher flow rates. As a result, a decision was made to test both the manufacturers' recommended printing temperature and 60 °C above the recommended printing temperature. The decision to increase print temperature by 60 °C for each material was based on the primary researcher's previous experience with polymer extrusion. The 60 °C increase in temperature boosted flow rates without degrading the polymer or creating the cool center effect at the mid-process point. Higher print temperatures are still possible, and potentially, even better volumetric flow rates, and thus, better print speeds could have been achieved. Note that all printing was done inside of a fume hood to avoid harmful fumes that can be produced by printing and may be produced in increased volumes at higher printing temperatures.

The test methodology was designed to identify scenarios where flow abnormalities would begin occurring in the third process of a four process test series. The assumption is that if the first two processes do not produce defects and the second two do produce defects then the first two processes are at speeds below the practical maximum average volumetric flow rate and the second two are above it. The practical maximum volumetric flow rate was assumed to be the average of all four process speeds. The average speed for the process group is the preferred expression of the practical maximum flow rate rather than the speed for the process group at which defects began to occur. There are two reasons for this. First, the speed that produced defects is, in theory, above the practical maximum, and second, print speeds vary even within a single process through accelerations and decelerations necessitated by object geometry.

C. Failure Modes

One of the challenges of establishing practical maximum average volumetric flow rates was in determining what failure looks like. There is not a lot of published material available discussing what levels of flow rate abnormalities could be acceptable for industrial printing. The printed objects produced by this research were inspected for different types of abnormalities. These abnormalities mainly included evidence of missing polymer in a printed track, polymer skipping a corner of the track, two tracks not connecting at a turn and weak adhesion between layers. The leftmost corner of Fig. 8 is missing polymer around the middle height of the test print evidencing that the polymer was too cool to be extruded from the hot end continuously at this speed. While Fig. 9 does not have obvious holes in extrusion around the middle height, there are smaller divots that correspond to sounds of the extruder motor skipping while printing. Another sign of failure was plastic not properly adhering to the previous layer and partially skipping a turn. Fig. 11 is a top view of the test print illustrating this failure.

Fig. 11. Top View of HIPS 305 °C

While the HIPS 305 °C test print shows less noticeable failure at the halfway point from the front view in Fig. 8, the inside of a turn shows plastic not hot enough to adhere to the previous layer causing skipping of part of the turn as depicted in Fig. 12 below.

Fig. 12. Close-up of Skipped Turns

D. Limitations

Multiple items and variables influence print speeds. The equipment used to run these tests is specified in this document. It is not expected that any set of equipment would achieve identical results due to other possible limiting factors such as a weaker extruder motor, lower extruder gearing ratio, a different nozzle size and more. During these tests, adjustments were made to the final testing equipment set to eliminate issues related to the maximum flow rate achievable that appeared to be caused by factors other than the hotend. Notably, the control board for the printer was changed to use newer, more advanced drivers for the stepper motors. Also, the extruder was changed to have dual drive gears, meaning gears grip the filament from both sides instead of one drive gear pushing filament against a smooth idler bearing. The final test equipment set produced results that seemed to demonstrate similar ranges of flow rates across materials, particularly in the high temperature group. This could indicate that the maximum flow rates achieved are indicative of the hotend's capability.

V. Conclusion

This research revealed practical maximum average volumetric flow rates for the given materials and hotend. As a result of this work, Slice can provide users with a better idea of the volumetric flow rates and related print speeds achievable with Mosquito Magnum+. Testing was performed in duplicate with repeatable results that eclipse the manufacturer rated capacities of virtually all hotends available on the market today. Similar testing could be done for all Slice hotend products and for additional materials as well as competitor products for comparison.

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