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Experimental Derivation of the Thermal Coefficients and Performance Observations of Heated Platforms in 3D Printing

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Abstract

Rapid prototyping and additive manufacturing through 3D printing has significantly impacted business, industrial, and research activities as a rapidly emerging technology whose significance continues to grow. This new technology has been shown to lower the manufacturing costs in a wide array of applications that range in diversity from manufacturing nuclear power plant components to multimaterials, and fabricating tissues and organs for human bodies to carbon fiber-reinforced parts at unprecedented rates for private jets [1]. The investigation of several heated platforms under operating conditions forms the basis for this paper from which the thermal coefficients of each product are experimentally derived. From this testing and derivation, intriguing observations regarding each platforms performance is presented.

Keywords: *3D Printing, Additive Manufacturing (AM), Fused Deposition Modeling (FDM), Manual Modeling Process, Heat Transfer, Thermodynamics, Thermal Coefficient*

1. Introduction

This paper documents and presents in depth testing of three heated platforms expanding upon the 2016 Ambient Systems, Networks and Technologies conference publication [2]. The results of further testing are the empirically derived thermal coefficients for each of the three platforms; the total energy draw for each heated platform, evaluated based on typical print times, with the observed flaws for each heated platform noted. Observed flaws are noted and investigated herein to substantiate test results documented by the SD3D Corporation. SD3D published a report in 2015 titled *Not all Heated Beds Are Created Equal* [8], which described the product testing of 6 different heated build platforms (HBP) available on the market. The research that was conducted by SD3D was based on running each of the 6 HBP's while recording the HBP's print surface behavior with a thermal imaging camera. Of the 6 platforms tested by SD3D, only one product was tested for this paper as well, the Prusa MK2B. The findings presented by SD3D and the observations presented in this paper, along with the noted temperature fluctuations across the MK2B's surface match nearly exactly. The validation that SD3D gave for why this product testing was worthwhile was attributed to large temperature differentials across a HBP's surface can cause delamination and marring of products either during cooling or during manufacture [8]. Though this was only one noted reason for developing the prototype initially, improving print quality for the RAPTER became a key asset as the project progressed. A review of several related papers indicate that only three heated platforms were tested at this time due to available products on the market. The products that were selected for testing in this paper were the prototype as defined in this investigation, the Prusa MK2B and a silicon rubber heated platform.

2. Content and Background

The prototype, Prusa MK2B and the silicon-heated platform selected were evaluated based on temperature diffusion, empirically derived heat thermal coefficients, energy draw and maximum temperatures reached. The testing methodology followed and as developed during the course of testing is presented in section 2.1 Testing Methodology.

The prototype is a proprietary implementation developed exclusively to satisfy requirements presented by the RAPTER 3D printer. The RAPTER 3D printer was an extrusion 3D-printer designed and prototyped at Embry-Riddle Aeronautical University for the academic year 2013-2014 robotics senior capstone course. The prototype is a 10” by 10”, insulated, aluminum heated platform. The prototype was designed for a 12V supply with a 4.46A current draw, resulting in a 53.49W power draw. During an earlier period, testing was performed in the high desert of Arizona and presented in the ANT 2016 manuscript; the current draw for the prototype was

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experimentally seen to be 4.2A. Both current draws and subsequent power draws are included as a basis for expected performance in the following testing.

The Prusa MK2B heated platform is an aluminum silkscreen heated platform that can either have a 24V or 12V power supply, depending on how the power input is wired. For comparability to the prototype, the MK2B was wired for a 12V input in the following tests. According to the online MK2B wiki the minimum suggested power supply for the MK2B is 12V at 15A or 180W.

The silicon rubber heated platform is designed and marketed for use with a 12V power supply and has a power rating of 150W. From the power and voltage rating the expected current draw is 12.5A. The expected power and current draws are given in Table 1 Expected Power Draw:

Name	Supply Voltage (V)	Current (A)	Power Draw (W)
Prototype	12	4.46/4.2	53.5/50
Prusa MK2B	24-Dec	15	180
Silicon Rubber	12	12.5	150

Table 1 Expected Power Draws

The current and power draw for each platform is listed in Table 2, where the anticipated results during the trials conducted for this paper are presented. However, none of the platforms performed as initially expected. The silicon rubber platform was the only platform to have a current draw close to what was expected, but other observations gave rise to print quality concerns. The expected current draw for the silicon rubber platform, listed in Table 1 was 12.5A, but the observed current draw, was 11.5A to 10.5A range, which is an increase of 8% to 16%. The MK2B, due to the supply voltage selected, drew significantly less currant than expected, but at a significant cost to overall performance. According to the MK2B wiki page the only referenced current draw for the MK2B is 15A, which is approximately ¼ of the anticipated current draw. The prototype also presented results that were not expected, both positive and negative surprises. Each observation is discussed further and also contributed to expanded testing during the research.

2.1. Testing Methodology

For commonality and accurate comparisons of the three heated platforms a common testing procedure was followed and adhered to during the course of the testing. Initially each platform was tested in ten-minute trials to simulate the warm up initiation period used by some 3D printers, however this was deemed inadequate due to some of the results seen with the MK2B and the silicon rubber heated platform. A ten-minute initiation window was also the time frame the prototype was designed to reach an operating temperature of 100^{o} Celsius in. The trials were extended to thirty minutes for the second and third rounds because of inconsistent surface temperatures initially observed and continuously noted throughout testing for the MK2B and silicon rubber platforms. The fourth round was extended to 60 minutes for the MK2B and the silicon rubber platforms only, due to concerns about the results noted in the second and third round. From the first round of testing the silicon rubber platform had significant temperature variations across the surface that were greater than reasonable error could justify, resulting in data sampled from multiple locations and recorded for two locations in particular. The reasonable error followed was a temperature differential greater than 10^{o} Celsius. The two locations chosen were approximately 2” apart and near the center of the platform, which would be where most objects being printed would be built. The goal of extending the trials duration was to determine if the heat would diffuse throughout the silicon rubber and MK2B platforms. The trial extensions also came about because of the maximum temperature obtained while testing the MK2B was typically the desired operating temperature for PLA and not the required temp for ABS. The MK2B during the first rounds failed to reach the expected operating temperature. The surface that the platforms were tested on was kept the same to keep the testing environment consistent. Keeping a common test surface between trials helps keep the coefficient of thermal conduction between the HBP being tested and the testing platform constant. The surface used for testing was a thermal glass platform that was later raised off of the table by 6”. The raised testing surface served two purposes; 1) prevent the electrical leads for the platforms from crossing and 2) prevent short-circuit conditions. This was a concern for the MK2B in particular because the leads had to be soldered before testing could commence. Secondly, the raised surface eliminated direct surface contact between the heated plate being tested and the workbench. Limiting the points of contact between the HBP being tested and the workbench limited the heat transferred through conduction to the lab bench.

After each platform was tested, it was relocated and set onto a granite countertop to expedite cooling. Moving the thermal glass to the counter as well was also done to cool the thermal glass down to room temperature again, making the starting temperature for each platform more consistent. As a result, this step significantly increased the testing time required per round for each platform. The trials conducted for all of the heated platforms were done over the course of a week. During each test period, the ambient humidity and temperature varied in calibrated step changes; ranging from 39% to 89% humidity daily and from 55^{o} to 95^{o} Fahrenheit. The equipment used for testing is listed in Table 2 below.

Equipment	Brand	Quantity
Power Supply	BK Precision 1688B	1
Temperature Probe	Extech Instruments True RMS Multimenter 430 w/ Thermocouple	1
IR Thermometer	Extech Instruments 42509 IR Thermometer	1
Digital Scale	Polder	1
Stop Watch	Apple IPhone 5S	1

Table 2 Listing of Equipment for Testing

The power supply and temperature probe referenced in Table 2 were used during the trials for all of the heated platforms. The power supply by BK precision was chosen for the ability to supply up to 18V and handle a maximum current draw of 20A. For precision and accuracy, the same leads and voltage setting were used during all trials conducted. The Extech Instruments multimeter 430 was selected because it provides the capability for a thermocouple probe attachment that provides service temperature readings. All of the temperature readings were recorded with the same thermocouple probe. The Extech Instruments IR thermometer was initially intended to collect and document each platforms temperature according to the radiation loss, but due to inconsistencies with the data, the IR thermometer was only used to support an observation without empirical data. The Polder digital scale was used to weigh each heated platform.

2.2. Energy and Heat Transfer

Referencing the ANT16 Conference paper published in March of 2016, the natural comparison was a logical approach to use experimental data and derive the thermal coefficients of each plate. Deriving the thermal coefficients presents more than just the percent differences between the three plates selected for further examination. Deriving the thermal coefficients with respect to different sampling times and with data collected over a period of time shows more realistic trends in each platforms performance. Deriving each platforms thermal coefficient also provides a material property for the product that can then be used to predict, with reasonable certainty, how each product will behave in similar environments. The thermal coefficient derived from the data collected is dependent upon two critical assumptions. The first, a steady state temperature is obtained for each platform during testing. The second is that the energy supplied will be equal to the energy lost, which would be equal to the energy of the system and thus neglecting parasitic losses. This assumption and resulting equation can be seen in equation (1):

$$\mathbf{P_{supply} = q_{loss} = q_{radiation} + q_{conduction} + q_{convection} = m \cdot c \cdot dt} \qquad (1)$$

Where P_{supply} is the power supplied in Watts, which is equation (2):

$$\mathbf{P_{supply} = P = V \cdot I} \qquad (2)$$

In order to make the association between equation (4) and equation (2), power had to be converted to the units of Joules. To convert the power supplied to each platform into the total energy supplied for each platform, the input voltage and current were multiplied by the trial duration; shown in equation (3):

$$\mathbf{P_{supply} \cdot dt = V \cdot I \cdot dt} \qquad (3)$$

Multiplying the supplied power by the duration that the power was supplied converts the units from Watts to Joules, making the association between system energy to supplied power valid.

$$\mathbf{P_{supply} = m \cdot c \cdot dt} \qquad (4)$$

The simplified equation in equation (4) is defined by the variables *mass m*, the *thermal coefficient c*, and the *change in temperature dt.* The mass that was used for each heated platform assumed that the energy dissipated to the thermal glass plate is accounted for in the *energy loss* $q_{conduction}$ therefore the *mass in grams, m* only incorporates the heated platform being tested.

An assumption that was used for the maximum desired temperature and contributed to the observer bias employed while scrutinizing the data and trends is that the desired operating temperature for a heated platform is 100^{o} Celsius. 100^{o} Celsius was further selected because RHP was designed to obtain and sustain 100^{o} Celsius while operating. The 100^{o} Celsius mark was chosen as an initial design parameter because it is within the optimal range for heated platforms to use when printing ABS products. 100^{o} Celsius is the optimal temperature for an ABS HBP because 100^{o} Celsius prevents the cooling layers of the product from cooling too quickly and allows the next layer printing to securely bond with the prior layer.

2.3. Rictor Heated Prototype (RHP)

While testing the RHP several observations were made: The first, was that the current draw was 1A larger than what the design calculations predicted, the design specified and prior testing showed. The second was that RHP has a more even temperature distribution across the entire surface, when compared to the data collected from the other platforms. RHP was designed to have a current draw of 4.5A, however during initial testing the current draw was consistently about 4.2A. During the testing conducted for this publication however, RHP had a constant current draw of 5.2A. This increase in the current draw, however unexpected, pointed out an oversight made during the design and prior testing. The oversight being that the calculation and initial testing were conducted in the mountains of Arizona at an elevation of 5000 feet, with a relatively low humidity. These latest rounds of testing were conducted at roughly 500 feet elevation in the Portland metropolitan area of Oregon City, with nearly double the humidity. As a result, the increase in the current draw and greater power draw is hypothesized to be due to an increased energy radiation and convection energy loss associated with atmospheric conditions.

Recorded test data provided in Table 3 are the current draw, supply voltage, steady state temperature, ambient temperature, the difference between steady state and ambient temperature, the trial time in minutes and the table mass. These values were utilized in equation (4) to calculate and solve for RHP's thermal coefficient for each trial.

Trial	Amps	Volts	Watts	SS Temp Deg C	Amb Temp Deg C	delta Temp Deg C	dt (min)	dt (sec)	Mass (g)	Thermal Coef
1	5.2	12	62.4	65	27	38	10	60	568	1.73
2	5.2	12	62.4	68	28	40	10	60	568	1.65
3	5.2	12	62.4	90	27	63	30	60	568	3.14
3	5.2	12	62.4	90	28	62	30	60	568	3.19
3.1	5.2	12	62.4	67	28	39	10	60	568	1.69
3.1	5.2	12	62.4	68	27	41	10	60	568	1.61
4	5.2	12	62.4	90	28	62	30	60	568	3.19
4	5.2	12	62.4	89	28	61	30	60	568	3.24
4.1	5.2	12	62.4	68	28	40	10	60	568	1.65
4.1	5.2	12	62.4	68	28	40	10	60	568	1.65

Table 3 RHP Data

The trials 4.1 and 3.1 are the first ten minutes of trials 3 and 4. These trials were used to compare the thermal coefficients derived from, and the temperature data gathered in the first two trials, to the thermal coefficients derived from and the temperature data collected in trials 3 and 4. Since these trials were conducted over the span of a week with large fluctuations in the atmospheric conditions, the effects of these fluctuations upon the prototypes performance were unknown. Comparing the resulting thermo coefficients shows that over the course of the trials, at the 10-minute time mark, the prototype consistently showed the same energy draw and energy losses. The prototype also showed consistent energy diffusion throughout the surface. The temperature differential from one corner of the prototype to the other, compared to the center of the platform was within 1 or 2^{o} Celsius. In terms of temperature control and margin of error when measuring RHP's operating temperature, would find a 1 or 2^{o} margin to be negligible. It is interesting to note that the maximum temperature reached by RHP was less than the calculations predicted and the design called for; the maximum temperature observed was 90^{o} Celsius. Since the current draw and ultimately the power draw for RHP was greater in Oregon and the maximum temperature reached was lower than in Arizona. The cause of this seems to be associated with the differences in climate and elevation, which is my working theory at this point in time. In terms of the design, these results that there are opportunities for further improvements; however, RHP could still perform with some ABS printers or PLA with the right temperature control settings. 90^{o} Celsius is the bottom end of the ideal operating temperature range for platforms used in ABS printers.

2.4. Prusa/MK2B

The second heated platform examined was the 200mm by 200mm aluminum heated platform designed by Prusa for the MakerBot 3D printer, the MK2B. This heated platform was selected both for its size, material and rated power supply. The MK2B at the time RHP was designed and built was considered for use in the RATPER 3D printer. After the recent rounds of testing, the choice to design RHP was validated again.

During the trial it became apparent that depending on how the MK2B is wired, either for 12V or 24V, determines the maximum steady state temperature the platform can reach. With the platform wired for a 12-volt supply, the maximum current draw is 3.6A, which in terms of power draw makes the MK2B a prime candidate. However, when the platform is wired for 12V, the steady state temperature reached is 70^{o} Celsius. This is the manufacturer's maximum temperature for the 3D printers incorporating PLA filaments. The data collected from testing the MK2B is presented in Table 4.

Trial	Amps	Volts	Watts	SS Temp Deg C	Amb Temp Deg C	delta Temp Deg C	dt (min)	dt (sec)	Mass (g)	Thermal Coef
1	3.1	12	37.2	63	32	31	10	60	185	1.00
2	3.3	12	39.6	66	30	36	10	60	185	0.91
2	3.3	12	39.6	38	28	10	10	60	185	3.29
3	3.35	12	40.2	70	29	41	30	60	185	2.44
3	3.35	12	40.2	40	29	11	30	60	185	9.11
3.1	3.35	12	40.2	62	29	33	10	60	185	1.01
3.1	3.35	12	40.2	40	29	11	10	60	185	3.04
4	190.5	12	2286	60	27	33	1	60	185	5.76
4	190.5	12	2286	47	27	20	1	60	185	9.50
4.1	24.6	12	295.2	52	27	25	1	60	185	0.98
4.1	24.6	12	295.2	42	27	15	1	60	185	1.64

Table 4 Prusa MK2B Data

As testing continued, the energy diffusion and temperature differential across the surface became more interesting. Specifically, temperature readings were recorded from two distinct areas due to a significant temperature differential. Taking a reading with the thermocouple about 2" down from the hole in the center of the plate would be around 65^{o} Celsius, however 2" above that same hole would only be 35^{o} to 40^{o} Celsius. This temperature gradient would increase as the test continued for about a quarter to half an hour. Part of the reason for extending the trial times to 30 minutes and 60 minutes respectively, was to determine if the gradient would gradually decrease over time or if it remained constant.

Throughout the trials, the temperature differential persisted for the MK2B, which brought up concerns regarding print quality due to temperature swings. These same concerns of print quality were also noted by SD3D in 2015 when they were testing the MK2B against their heated build platform. SD3D observed that the center of the platform could be as much as 20^{o} Celsius differential across the platform [8]. The thermal images that SD3D presents shows 'cold' spots at the corners of the heated build platform. Though their findings showed the same differential, their findings concluded that the differential was over a greater surface area than the test results in this paper discovered. The SD3D conclusions presented, are based solely on the radiation recorded by thermal imaging confirm and are in agreement with the conclusions based on the test data as recorded in this paper.

Since the temperature swings recorded, the thermal coefficient is calculated for each recorded area rather than average measurement. The cause of such a large temperature differential seems to be due to the etching and the thickness of the platform. The platform was designed to dissipate energy away, not retain energy. The issue seems to be that the rate of energy loss due to convection and conduction is greater than the rate of energy diffusion throughout the platforms volume. The rate of energy loss is also greater than or nearly equal to the power draw.

2.5. Silicon Rubber

The third platform to be examined and tested was 200mm by 200mm silicon rubber HBP. A silicon rubber platform was selected because of how common they are to find on the market and their versatility. These HBP work for most filament types and have rapid rise times. One particular silicon rubber platform had a rise time of 1 minute from ambient temperature to 100^{o} Celsius. Rapid rise times and the ability to accommodate customizable print temperatures, leads to a significantly larger power draw and energy losses. The increased energy losses seem to be due to the emissivity of the silicon rubber, which leads to a much greater radiation loss. Through the use of an infrared red (IR) thermometer the surface temperature of the silicon rubber platform tested was several hundred degrees centigrade. Because the IR thermometer was displaying readings several magnitudes greater than the thermocouple touching the surface, the IR thermometer was determined to be giving false readings. However, when holding the thermocouple to the surface, the amount of radiation felt by the operator coming from the silicon rubber platform was significantly greater than the radiation emanating from the MK2B or RHP. In some instances, the IR thermometer would be registering 300^{o} to 400^{o} Celsius for the silicon rubber platform, but the thermocouple touching the surface would only be registering 80^{o} or 90^{o} Celsius. Because the IR sensor's readouts would also fluctuate by 10^{o} or 20^{o} almost instantaneously, this provided enough concern regarding the data's reliability to warrant excluding the IR sensor's data; the thermocouple's data was exclusively relied upon for calculations.

Trial	Amps	Volts	Watts	SS Temp Deg C	Amb Temp Deg C	Delta Temp Deg C	dt (min)	dt (sec)	Mass (g)	Thermal Coef
1	11	12	132	100	32	68	5	60	115	5.06
2	11	12	132	90	33	57	10	60	115	12.08
3	10.8	12	129.6	120	28	92	30	60	115	22.05
3	10.8	12	129.6	102	28	74	30	60	115	27.41
3.1	10.8	12	129.6	90	28	62	10	60	115	10.91
3.2	10.8	12	129.6	98	28	70	10	60	115	9.66
4	585	12	7020	123	27	96	1	60	115	38.15
4	585	12	7020	123	27	96	1	60	115	38.15
4.1	70.2	12	842.4	95	27	68	1	60	115	6.46
4.1	70.2	12	842.4	85	27	58	1	60	115	7.58

Table 5 Silicon Rubber Data

3. Conclusion

After testing and analyzing the performance of each of the HBP listed in Table 6: HBPs Tested, against one another, RHP's design for the unique application of the RAPTER is proves to be the superb design. From the initial design criteria and observations, to the tests performed as reported herein, RHP has shown performance improvements over commercially available HBP available in today's market.

Product Name	Material Type	Notes
Rictor's Heated Prototype (RHP)	Aluminum	3Dreamers
Prusa MK2B	Aluminum	RepRap [4],[11]
Signswise	Silicone Ruber	Signswise [12]

Table 6 HBPs Tested

As per the literature, several other 3D printing research and development teams, most notably by SD3D, are in agreement and support the test results herein. The RHP offers the most efficient and rapid energy diffusion of the three options. The silicon rubber platform only demonstrated an even temperature distribution across the surface after 45 minutes to an hour of continuous operation, while the MK2B consistently had a temperature differential that was not exhibited by the RHP. At approximately the ten-minute mark for each trial, the energy distribution for RHP was even. Though the silicon rubber platform could reach operating temperatures that were twice that of the MK2B and 50% greater than RHP, RHP required less than half of the power the silicon rubber platform needed to operate, which for the application of the RAPTER was and is key to the RAPTER's performance. Compared to the MK2B and the silicon rubber platforms, both of which are only 8" x 8" platforms, RHP is larger and has a smaller temperature differential over the total 10" x 10" profile; about 2^{o} Celsius. RHP reaches an operating temperature that is 38.8% greater than the MK2B's, with a 39% greater energy draw and has a 36% larger surface area, while using the same 12V source. When compared to the silicon rubber platform, RHP reaches a maximum temperature that is 18% lower, while consuming 52.7% less power and has a 36% larger surface area as well, with the same 12V source. Suggestions for future work include expanding the number of products to include different manufacturers and varying selected parameters to determine performance.

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