International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8, Issue-1S5, June 2019

Vacuum System Assisted Fdm – Characteristic of Heat Transfer using Finite Element Analysis

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ABSTRACT: Fused deposition modeling (FDM) process is one of the most efficient and used additive manufacturing technologies. For years, building functional components with good mechanical strength has been a difficult task. Generally, FDM process is operated in a room with or without an enclosure to produce physical polymer components. Therefore, the inconsistencies from different environmental factor such as temperature and air quality have indirectly affected its quality build. Vacuum technology has been used in the wide area of applications by creating an empty space of matter. However, there is no investigation of FDM operated in a vacuum environment. This paper aims to study the behaviour of the temperature inside a vacuum assisted FDM by performing finite element analysis. A heated nozzle and heated bed will be placed inside a vacuum chamber with a constant heat source and the initial temperature set at room temperature. The pressure range from 30 inHg (1 atm) to 1 inHg will be the manipulated variable. The result shows that as the pressure decreases, the transient heat transfer (natural convective heating) also reduced and the velocity of air flow became more consistent. This study was able to prove how different vacuum pressures can affect the heat inside a vacuum chamber. Results from this study can be used to further analyse the mechanical strength of vacuumed printed components in actual experimentations.

KEYWORDS: Fused Deposition Modeling, Vacuum System and Finite Element Analysis.

1. INTRODUCTION

In the early 1980's, rapid prototyping created layer by layer 3D objects using computer-aided design (CAD) model to produce a prototype components or models. This technology brings to one of the earlier additive manufacturing processes by actualizing the creation of functional printed components rather than just a model [1].

Additive manufacturing (AM) is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [2]. Fused deposition modeling (FDM) is one of the most frequently used in additive manufacturing process [3]. FDM starts by flexible thermoplastic filaments. The filament will be extruded into the heating block and pass through the small nozzle tip to deliver molten thin thread onto the platform layer by layer in increasing height [4]. AM aims for mass production of end-use products rather than just a prototype to save cost and time [5]. However, the limitation of the mechanical strength is one of the drawbacks to produce functional working components [6].

Vacuum technology has been used in many areas of studies and applications such as resin infusion molding [7], die casting [8] and drying process [9] due to the vacuum's unique capability to change the environment by decreasing the atmospheric pressure to suit the specific condition of the studies or applications. The vacuum will prevent or reduce the convection process from occurring and heat loss from the source can be maintained for a longer period of time depending on vacuum range. As a result, no thermal energy will be able to transmit easily by convection across the vacuum environment [10-11].This paper presents a simulation study to observe the behaviour of heat transfer in a vacuum environment and to investigate its feasibility in FDM operations. A chamber internal size of 350 x 390 x 400mm will be the domain of a simulation study. The constant heat source from heat bed (100 °C) and nozzle (260 °C) will transfer the heat throughout the chamber. A vacuum range from 30 inHg (1 atm) to 1 inHg will be the process variable in this study. Finite element analysis will be conducted to determine the appropriate range of pressure for FDM operations. For future references, this study will be used to provide simulation data with a comparison on the actual data to support the core of this study.

Revised Manuscript Received on June 1, 2019.

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2. BACKGROUND STUDY

2.1 Fused Deposition Modeling

The extrusion-based system is the most popular technology used in the additive manufacturing field [12]. FDM is one of the common extrusion-based AM systems developed by Stratasys [13]. FDM works by drawing 3D-CAD data which will be converted into STL file. The software will then horizontal sliced into layers with desired build parameters. If required, support structures will be generated as well. Next, the FDM machine starts by allowing flexible polymer filament to be extruded through a heated nozzle with the constant temperature value depending on thetype of material. The extruded material from the nozzle will be the in thin treaded layers which will deposits onto a previously built layer on the heat bed in 2 dimensional (x-y) axes. The new layer will cool downs and solidifies to bond in between each layer. Depending on FDM machine type, either nozzle or platform will move in thez-axis to allow another new layer to deposit again [4, 14]. One of the major advantages of having FDM is the possibilities to create complex geometries and cavities. The huge design freedom would be difficult for conventional manufacturing methods [15]. As the most applicable process for AM, FDM provides ease of operation, inexpensive machinery and elimination of tooling [16]. Overall, FDM offers advantages in terms of time and cost in manufacturing custom products. In contrast, FDM is unable to provide satisfactory mechanical properties of the products [17]. Most studies by other researchers found out that the significant reason is the incomplete bonding of layers between the filaments. Normally the extruded filaments solidified too fast thus prevented the complete bonding to occur. The thermal energy loss is through conduction of solids and convection of air [18-20].

Vacuum System

Vacuum is a space where there is no matter, a space that is empty containing no particles [21]. Although absolute vacuum is currently impossible to achieve, vacuum term has been used to define as spaces of thevolume containing a lower pressure than the atmospheric pressure [22]. Generally, the atmospheric pressure in 30 inHg(101,325 Pa) contains particles of air that is constantly colliding with each other. A wide range of applications in studies and industries uses a different range of vacuum from low to ultra-high level. For example, in one atmospheric pressure, the molecules will keep on bombarding to transmit energy. The molecules are close to each other and travel in any direction, hitting on each other to pass the energy around. Hence, the energy cannot be transferred when there is no medium for the collisions to occur. Similarly, by lowering the atmospheric pressure, the smaller quantity of molecules will be able to travel freely with alow chance of collisions [23]. In relevant to this study, the change of physical properties of air due to vacuum causes different thermal behaviour. Heat losses through convection can be reduced due to the absence of air particles [22-24].

2.2 Heat Transfer

Energy exists in many forms is capable of altering the state of the substance which results in the work performance [25]. Thermal energy or heat energy is another form of energy. Thermal energy is defined as energy that flows from one body to another body when there is a difference in temperature and stops when equilibrium temperature achieved. Thermal energy is correlated with thetemperature of the system. As the heat energy increases, temperature increases and vice versa. Although both seem to be similar, they are not one and the same [26]. Basically, thetemperature is affected by the amount of heat energy, the mass and the nature of the object. For example, the polymer will require more thermal energy than metal to rise towards a specific temperature as both have which different in conductivity.Heat transfer of thermal energy in one body to another happens through several ways; mainly thermal conduction, convection and radiation [22]. This study will focus specifically on heat transfer in natural convection only since conduction and radiation are negligible in this case. Conduction cannot be carried out since the thermal energy from the nozzle extruded filament will transfer to the heat bed platform and to the rest of the FDM machine body even in the vacuum state. Radiation cannot be carried out for this study because radiation transfers heat through electromagnetic radiation and hence does not require any medium to travel. Thermal radiation will be emitted as long as matter with atemperature higher than absolute zero [27]. Convection will occur when there is a liquid or gaseous medium exists for heat transfer. In natural convection, the change of density of fluid or gases will cause the motion of thefluid. For instance, lower density hot air rises while higher density cold air dense builds a thermal convection [28]. Natural convection heat transfer for vertical plates in equation 1 was conducted with anaccuracy of RA>10^9[29].

$$\bar{N}u_L = \left\{0.825 + \frac{0.387 Ra_L{}^{1/6}}{\left[1 + (\frac{0.492}{Pr})^{9/16}\right]^{8/27}}\right\}^2 \qquad (1)$$

Since convection will only happen when there is a medium of fluid or gases, there will be no heat transfer if the medium is eliminated through an absolute vacuum. However, in practical

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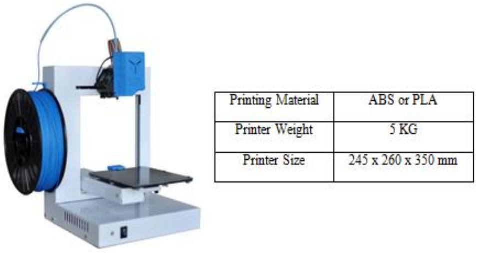
application [30], heat convection can be significantly reduced depending on the degree of vacuum. A dimensional relation in equation 2 is used to approximate the heat convected to the air different pressure [31].

$$q_c = 0.2426\frac{(\gamma+1)}{\gamma-1}\frac{P}{\sqrt{MT_g}}(T_s - T_g) \qquad (2)$$

3 METHODOLOGY

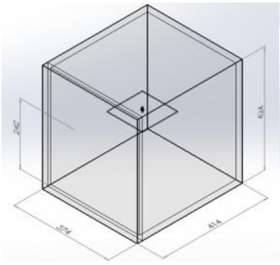
This study requiresa 3D CAD of the vacuum chamber [32]. The system will mainly have a chamber, nozzle and heat bed. Up Plus 2 was chosen as the FDM machine shown in Figure 1.



Printing Material	ABS or PLA
Printer Weight	5 KG
Printer Size	245 x 260 x 350 mm

Figure 1: Up Plus 2 FDM machine

A rectangular chamber was designed to place the Up Plus 2 FDM machine inside it. The rectangular shape chamber is chosen due to the FDM's close rectangular shape built. The shape will minimize the volume of the chamber, thus increase the air efficiency removal rate and improve the chamber's strength. Inside the chamber, the rest of the FDM machine body was omitted except for the nozzle and heat bed for the sole purpose of monitoring heat transfer. Based on the measurement of heat bed and nozzle printing above the table, their position is fixed inside the chamber. Figure 2a shows the dimensions of a vacuum chamber as well as the placement of the nozzle and heat bed inside it. The inner dimensions measured by 350 x 390 x 400 mm with 12 mm thickness. The heat bed and nozzle were placed above the chamber surface by 242 mm. Figure 2b shows the 0.4 mm nozzle and 140 x 140 x 3 mm heat bed.



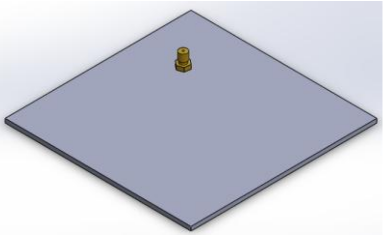


Figure 2a: Dimensions of vacuum chamber
Figure 2b: The nozzle and heat bed

Finite element analysis was done using SolidWorks Flow Simulation. It will be used to observe and study the heat transfer in an internal environment. During pre-preparations of flow simulation, 3D CAD models of the chamber, nozzle and heat bed were inserted. Input data for the SolidWorks Flow Simulation are shown in Table 1.

Table 1: Input data for simulation

Input	Value
Simulation physical time	3600 seconds
Time step interval	60 seconds
Gravity	-9.81 m/s^2
Air pressure	30, 20, 10, 5, 1 inHg
Air velocity	Steady state
Air type	Laminar and turbulent
Wall condition	Adiabatic wall
Initial temperature	20.05°C(default)
Constant Nozzle/Heat bed temperature	260/100°C

Default SI unit is used in this simulation. The analysis type is set as internal for the simulation to specifically cover inside the chamber and ignore the external environment. The FDM operations will be carried out for one hour with every one minute time step interval and a gravity of -9.81 m/s^2. Next, steady state air gases with laminar and turbulent will be selected. The wall condition will be set to adiabatic so no heat is gained or lost by the chamber system. The room or initial temperature is determined by SolidWorks default temperature, 20.05 °C (293.2 K). Under thermodynamic parameter, the parameters are pressure versus temperature with a pressure of 30 inHg and 20.05 °C as initial temperature. The simulation will be repeated with different pressure ranges of 20, 10, 5, and 1 inHg. The nozzle (260 °C) and heat bed (100 °C) are set with constant temperature value. The desired output is observed on the contours, vectors and streamlines on how the heat travel inside the vacuum chamber during different respective pressure range. Furthermore, a chart of temperature and time will be generated and analysed as well. Hence, this study will be able to prove how different vacuum pressures can affect the heat inside a vacuum chamber.

4 RESULTS AND DISCUSSION

Finite element analysis was carried out to study the behaviour of heat transfer in a vacuum environment and to investigate its feasibility in FDM operations. In steady state, five different vacuum pressure ranges were simulated and the cut plot result on 60th minutes is shown in
Figure 3.

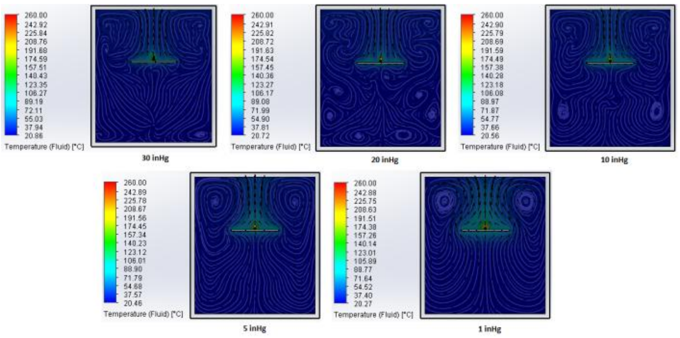


Figure 3: Thermal flow in 30, 20, 10, 5 and 1 inHg

From the five simulations, the air flow started from the heat source was dispersed upward, outward and downward is an effect caused by gravity. Hot air rises and draws cool air behind it. However, it can be clearly seen that the air flow patterns were different from each other. This reason is that the air in a vacuum system is divided into three states, vicious, intermediate and molecular. It happens when the atmospheric pressure is brought into the higher vacuum. The simulation started with 30 inHg equivalent to the one atmospheric pressure. On this level, the free mean path of the air particles is very small thus an irregular and non-parallel thermal air flow (flow of gas is limited by its viscosity) can be seen due to the fact at atmospheric pressure; the air particles create collisions. Hence it creates random movements in any direction. Consequently, the irregularities of thermal flow will affect the print quality during FDM operations. In the next simulation, the vacuum level will be increased by decreasing the pressure to 20 inHg. The thermal air flow pattern is now different compared to 30 inHg as the particles began to reconstruct its turbulent flow in a viscous state. When the velocity exceeds at certain values, the flow is turbulent, showing non-parallel and the directions were affected by any obstacles. Starting from 10 inHg to 5 inHg laminar flow can be seen from the simulation. Laminar flow occurred during lower velocities and showed parallel layers. The pattern began to show regularities. The free mean path is similar to the dimensions of the chamber; the flow is in between the viscosity and molecular phenomena; called as intermediate flow. The optimum flow can be seen from 1 inHg. The flow is smooth from both sides and almost parallel in each layer. The thermal flow rises up and down without disturbance hence would be the ideal pressure for FDM operations. The air inside the chamber has a molecular density that is involved with pressure. The temperature difference rate across the chamber is increased by the heat source and pressure. A graph between minimum temperature and physical time in group charts by the parameter is plotted as shown in Figure 4.

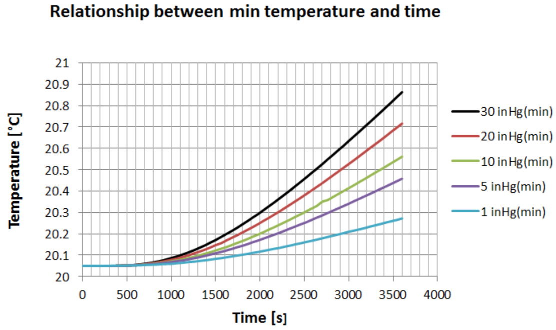


Figure 4: Thermal flow in 30, 20, 10, 5 and 1 inHg

The effect of the variable pressure on temperature is displayed in this figure. Multiple data of 60 minutes with 1-minute interval produce the results. Starting approximately from 600 seconds, the heating curve began to deviate and continue to grow in the gap. As prospected, when the pressure decreases, the minimum temperature decreases. As observed from Fig 3, at 1 inHg, the more yellowish colour was found surrounding the heat source compared to the rest. This is because the convective heat transfer is decreased due to the little medium of gases to collide and transfer its heat energy to the surrounding. The trapped heat near the heat source will influence the bonding of layers of the filaments for a period of time.

5 CONCLUSION

Heat transfer efficiency through convection is affected by air pressure. The lower pressure reduces the heat transfer from the heat source to the cooler area. Starting from 10 inHg till 1 inHg, the flow lines are smooth, parallel and curved gently whereas 20 inHg and above shows complex turbulent flow. The proper thermal without disturbance will improve FDM's operations by providing the ideal environment. Convection is caused by density variations of gas molecules. The air surrounding inside the chamber has a molecular density that relates to its pressure thus causes various convective heat transfer. At low pressure, the insufficient medium for the particles caused the inability for heat transfer to the colder area. For that reason, the minimum temperature does not rise up exponentially and the heat will be maintained for a longer period of time which subsequently improves FDM printed components quality in terms of layer bonding. Besides, the environment is much more ideal due to the cleanliness. To sum up, during FDM process, the environmental factor such as heat transfer can be controlled using a vacuum system. Based on finite element analysis, the appropriate range of pressure is between 5 inHg to 1 inHg. In future, further optimum pressure value has to be determined although this study has been done to find the optimum pressure range. Actual experimentations are required to analyse the

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mechanical strength of vacuumed printed components.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Universiti Teknikal Malaysia Melaka (UTeM) for the scholarship of ‘UTeMZamalah Scheme’ and the Ministry of Higher Education Malaysia for awarding the Fundamental Research Grant Scheme (FRGS) grant number FRGS/1/2015/TK03/FKP/02/F00282.

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