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ANALYSIS ON TEMPERATURE SETTING FOR EXTRUDING POLYLACTIC ACID USING OPEN-SOURCE 3D PRINTER

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ABSTRACT

The Rapid Prototyping (RP) technology has been developed since its original introduction, leading to a significant improvement in the manufacture of high-quality finished products. Fused deposition modeling (FDM) is a RP technology that has been widely used because of the flexibility of the FDM process. Despite the popularity of the FDM machines, cost remains a major issue, motivating the development of low-cost open-source 3D printing. However, the system and process of open-source 3D printing needs to be investigated, particularly along the highly complex liquefier; observation of the material flow inside the liquefier is essential for this purpose. This paper examines the temperature distribution of the liquefier and the flow behavior of the material inside the liquefier using finite element analysis (FEA). The liquefier temperature must be at 190 °C because higher temperatures cause the material to burn and lower temperatures may be detrimental for the extrusion process. Therefore, this study focuses on identifying the optimum printing temperature for the widely used polylactic acid (PLA) filaments. A new cylindrical liquefier design has been proposed to achieve a better heat distribution, and an optimum printing temperature of 190 °C (463.15K) has been suggested for extruding PLA material using open-source 3D printing.

Keywords: Open-source 3D printing, liquefier design, temperature distribution, polylactic acid, finite element analysis.

INTRODUCTION

Similar to other technologies, rapid prototyping (RP) has been subject to research aiming at making this technology more accessible, affordable, and compatible with the current industrial processes. Since the 1980s, RP technology has shown considerable development and has made a significant impact on fabrication processes used in the industry [1]. The FDM process is initiated when the thermoplastic material in the filament form is fed through the liquefier, pushed by the motor, and melted. The melted filament is then extruded by a nozzle and solidified in a layer by layer growth process until the fabrication is completed [2].

The current market for FDM is dominated by Stratasys, Inc., with 15,000 Stratasys FDM sold, which covers 41.5% of the entire market [3]. FDM 3000 is a popular FDM Stratasys model that has been widely used for research. For example, Ramanath *et al*. [4] used the FDM 3000 machine to study the melt flow behavior of a PCL material and observed a pressure drop along the original FDM 3000 liquefier using finite element analysis (FEA). Studies of melt flow of an ABS-Iron composite and the extrusion of medical-grade polymethylmetacrylate (PMMC) material have also been conducted using the FDM 3000 model. [5-6].

Open-source 3D printing can be used for manufacturing when cost is of utmost importance, for example, using the well-known low-cost RepRap (Replicating Rapid Prototyper) open-source 3D printer [7]. Further development of open-source 3D printing is therefore highly important. However, to date, little research has been conducted to determine the performance of the open-source 3D printing process. The latest study has focused on dimensional accuracy and has been performed using a MarketBot 3D desktop printer [8]. This particular machine shows a significant deviation in product dimensions from the input CAD design geometry that is caused by the printing process parameters. Detailed investigation is very essential on the printing setting to have consistent material properties as well as geometries. Other studies have been done using open-source 3D printer regarding the impact of process parameters on mechanical properties [9]. Both studies focus on the controlling the process parameters but not on the issues of controlling the printing temperature.

The present study focuses on determining the temperature distribution along the liquefier and the optimum setting temperature for extrusion of PLA in open-source 3D printing. The optimum setting temperature means the material inside the liquefier must meet the melting temperature of the PLA material, which is around 160 °C. Controlling the temperature within the melting point of PLA material is very crucial. The temperature inside the liquefier should be kept as low as possible because burning of the material leads to the appearance of a residue in the liquefier chamber and contamination of the remaining material [2].

The complexity of the liquefier means that it is essential to analyze the temperature distribution along the liquefier to have a clear understanding of the melt flow of the material that affects the stability of the extrusion process and can compromise the final product. The complexity of the liquefier is due to the unevenness of the heat flux originating from the heating element. The heating element is set to control the temperature of the system, and a thermocouple is embedded in the liquefier to

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detect the temperature. While any temperature difference between the actual and set temperatures detected by the thermocouple will lead to an adjustment by the system to eliminate this difference, there is a time delay between the temperature difference detection and the temperature adjustment so that the temperature inside the liquefier is not changed instantaneously [10]. In addition, an optimum temperature must be maintained inside the liquefier to produce a better extruded product and the liquefier temperature must be carefully observed to ensure that the temperature is in the optimum range. For this study, the optimal temperature is around 160°C (433.15K), which is identical to or slightly lower than the melting point of the PLA material.

Our investigations show that the effect of the incorrect temperature along the liquefier during the time period of the temperature adjustment can be minimized by increasing the heat transfer rate through the modification of the liquefier design. The specific printing temperature for the extrusion of the PLA material in the open-source 3D printing system developed for this research has also been suggested.

METHODOLOGY

A new open-source 3D printing system has been developed for this research. A low-cost computer-controlled machine with high accuracy for three axes (x, y, and z direction) is designed using a four high-accuracy stepper motor to simultaneously move the tool holder and worktable in three directions via a leadscrew. Repetier-Host Software is used as firmware; this software is freely available online and is highly suitable for research purposes. Figure-1 shows the original liquefier design used in this research. The methods of this study fall into two main categories:

- Temperature distribution in the liquefier design
- Flow behavior of the PLA material inside the liquefier

Finite element analysis has been used to investigate the temperature distribution as well as the flow behavior of the PLA material and analysis of the obtained results.

a) Temperature distribution on the liquefier design

3d modeling and mesh generation

The mesh for the liquefier modeling is generated using the tetrahedron method with a combination of high smoothing and fine relevance center to obtain the optimal result shown in Figure-2.

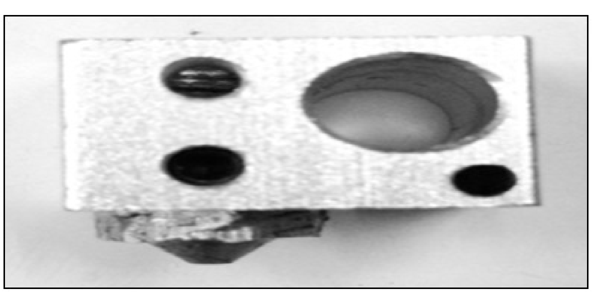

Figure-1. Original liquefier design.

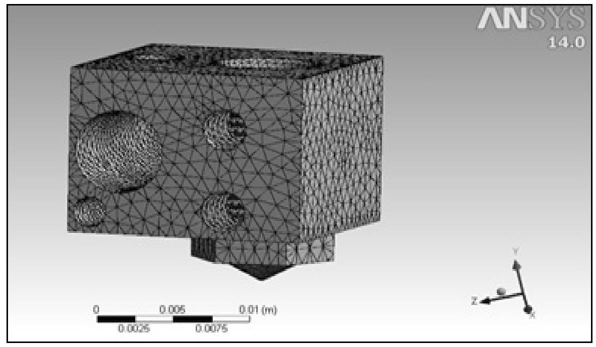

Figure-2. Mesh generation using the tetrahedron method.

Boundary conditions

Boundary conditions must be set up for the simulations, and several simulation parameters must be determined. Heat convection occurs around the liquefier entrance and at the nozzle exit; this is simulated using the convection coefficients (h) of 10 W/m2K and 100 W/m2K at the liquefier entrance and nozzle exit, respectively [3], [11]. This parameter value is chosen to represent the worst-case scenario, as the heat at the nozzle will be transferred to the filament during the extrusion process

In these simulations, aluminum (k = 200 W/mK) and copper (k = 401 W/mK) are used to represent the liquefier body and nozzle, respectively. The temperature of the system that is detected by thermocouple is set to 260°C (533.15K). These conditions are used for the cylindrical design as well. Figure-3 shows the boundary conditions for the simulation.

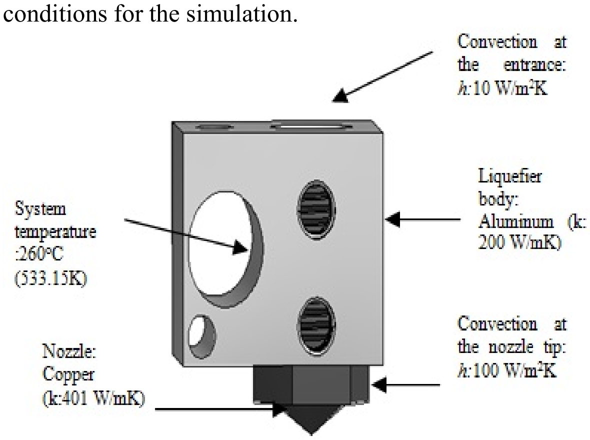

Figure-3. Boundary conditions for the simulations.

b) Flow behaviour of the PLA Material inside the liquefier

The geometry inside the liquefier is designed in a 3D model to observe the flow behavior of the material. The geometry covers the space from the inlet to the outlet nozzle. The 3D model design for the FEA simulation is shown in Figure-4.

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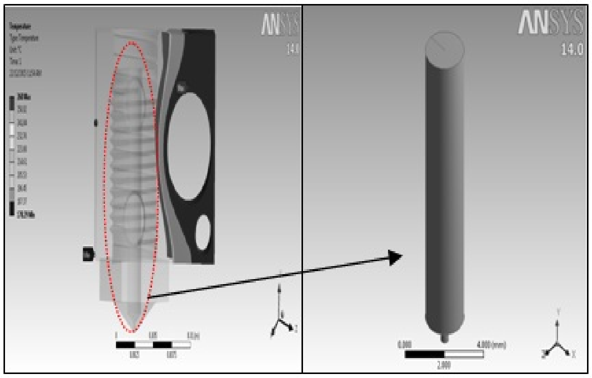

Figure-4. 3D model liquefier design for FEA simulations.

FEA simulations

FEA Simulations for the simulations, the flow of the material is considered to be laminar, the velocity at the wall through the liquefier is considered zero because the melt is assumed to adhere to the wall, and the liquefier temperature is assumed to be constant because the liquefier chamber is isolated [10, 11]. The specific heat, thermal conductivity, density, and melting point values of PLA are 1800 J/kg-K, 0.13 W/m-K, 1.25 g/cm3, and 160 °C (433.15K), respectively, and are used as the material parameters in the FEA simulations.

Boundary conditions

The fluid flow mode is used in the FEA as the solution method. FEA simulations are started from the inlet with the inlet velocity, and the outlet is set to be the pressure outlet. The temperature is set in Kelvin (K) at the inlet, at the walls, as well as at the outlet nozzle, representing the final temperature for the extrusion process. The diameter of the filament, D, is 1.8 mm, representing the liquefier diameter, and the diameter of the nozzle, d, is 0.4 mm. The boundary conditions for the simulations are shown in Figure-5(a) and Figure-5(b).

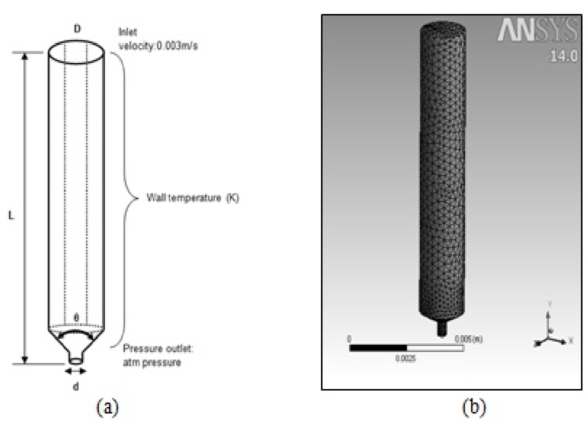

Figure-5(a). Boundary conditions and **Figure-5(b).** Mesh generation for flow simulations.

RESULTS AND DISCUSSION

a) Temperature distribution on the liquefier design

Figure-6 shows the results obtained for the temperature distribution at 1 s. The maximum temperature is shown in the red zone, and the minimum temperature is shown in the blue zone. The minimum temperature is 178.29 °C (451.44K). The exact temperature inside the liquefier chamber and at the nozzle tip, which is considered as the outlet temperature can be referred in circle shown in Fig. 6. Convection occurs at the entrance of the liquefier and at the nozzle tip, causing heat loss [18]. This phenomenon must be observed carefully because it will affect the flow stability of the filament along the liquefier.

Figure-6 shows that the temperature along the liquefier decreases from the green zone where it is approximately 223.69 °C (496.84K) to the blue zone where it is approximately 196.45 °C (469.6K). The lowest temperature is obtained at the nozzle tip because the convection effect is the strongest at the nozzle tip. The outlet temperature is the final extruded temperature before the material leaving the nozzle is deposited. The simulations show that this temperature is around 196.45 °C (469.6K).

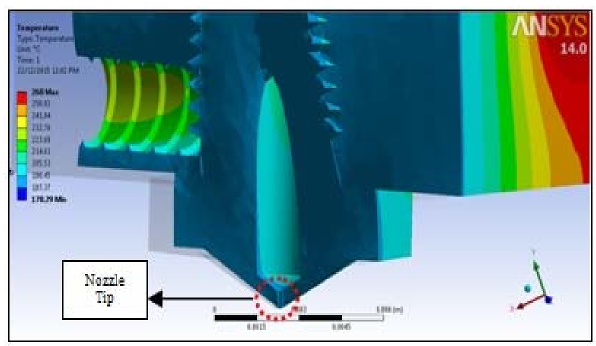

Figure-6. Temperature at the nozzle tip.

Practically, the liquefier of 3D printing can be heated to a temperature of 260 °C (533.15K), which is actually the temperature detected by the thermocouple and is not necessarily exactly equal to the temperature inside the liquefier. Determination of the temperature inside the liquefier can therefore significantly contribute to the better understanding of the material behavior inside the liquefier chamber.

During the deposition, a steady state and isothermal conditions are assumed with the temperature at the end of liquefier being equal to the temperature of the deposited material [10]. By considering the temperature to be constant during this time period, as found in Bellini's model, it is possible to estimate the pressure drop starting from regions A, B, and C shown in Figure-7.

$$\Delta P_A = 2L_a\left(\frac{v}{\varphi}\right)^{1/m}\left(\frac{m+3}{(D/2)^{m+1}}\right)^{1/m} \quad (1)$$

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$$\Delta P_B = \left(\frac{2m}{3\tan(\beta/2)}\right)\left(\frac{1}{d^{3/m}} - \frac{1}{D^{3/m}}\right) \times \left(\left(\frac{D_1}{2}\right)^2 (m+3)2^{m+3}\right)^{1/m} \quad (2)$$

$$\Delta P_C = 2L_B \left(\frac{v}{\phi}\right)^{1/m} \left(\frac{(m+3)(D/2)^2}{(d/2)^{m+3}}\right)^{1/m} \quad (3)$$

where m and Ø are material constants, v is the entrance velocity of the filament, **D** is the liquefier diameter that represents the filament diameter, **d** is the diameter of the outlet nozzle, and **La** and **Lb** are the respective lengths of regions A and C, as shown in Figure-7.

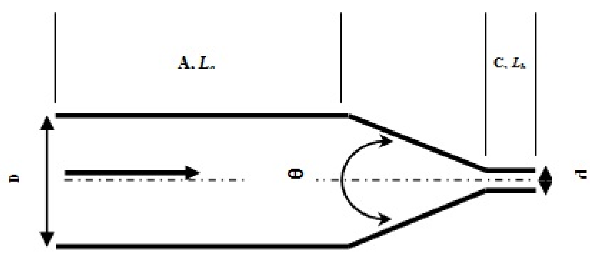


Figure-7. Liquefier region for FDM extruder (Adapted from [10]).

The flow of the material inside the liquefier is considered to be in a steady state condition until the flow rate is changed, disrupting the flow and transitioning to the unsteady state. The material will be in an unsteady state as the temperature drops, and consequently, the amount of the new material fed into the liquefier and the heat flows need to be increased. The system will continuously adjust the power supplied to the heating element according to the temperature set in the system and the value detected by the thermocouple. Therefore, there is a time delay in the response that affects the flow of the material inside the liquefier. When the flow is nonisothermal, the temperature dependence of the viscosity as well as the shear-rate dependence must be considered [10]. Therefore, the following model can be proposed:

$$\Delta P_A = 2L_a \left(\frac{v}{\phi}\right)^{1/m} \left(\frac{m+3}{(D/2)^{m+1}}\right)^{1/m} exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (4)$$

$$\Delta P_B = \left(\frac{2m}{3\tan(\beta/2)}\right)\left(\frac{1}{d^{3/m}} - \frac{1}{D^{3/m}}\right) \times \left(\left(\frac{D}{2}\right)^2 (m+3)2^{m+3}\right)^{1/m} \times exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (5)$$

$$\Delta P_C = 2L_c \left(\frac{v}{\phi}\right)^{1/m} \left(\frac{(m+3)(D/2)^2}{(d/2)^{m+3}}\right)^{1/m} exp\left[\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (6)$$

where T is the working temperature and Tα is the temperature at which m and Ø are calculated [10, 17].

Examination of the equations shows that the effect of the temperature makes a significant contribution to the pressure drop. As mentioned above, there is time delay in the adjustment of the temperature due to the thermal inertia of the liquefier system [10]. Considering this, some adjustment is required in the original liquefier design to increase the heat transfer to the liquefier for minimizing the time delay as well as reducing the pressure drop. By changing the shape of the liquefier to the shape shown in Figure-8, the heat transfer can be increased, minimizing the time delay and increasing the stability of the extrusion process.

Our simulation showed that the cylindrical shape results in a better heat transfer rate than the square shape. The minimum temperature in the dark blue zone is around 216.39 °C (489.54K). Here the temperatures along the liquefier wall and at the nozzle tip are the important parameters and are around 226.08 °C (499.23K); this is higher than that in the previous design and implies that the heat transfer rate has been improved. This is crucial because the time of adjustment when the new material is fed and fast heat transfer through the liquefier are essential for maintaining a constant viscosity of the material and reducing the pressure drop [10]. Thus, maintaining the liquefier temperature as constant as possible is vital for the development of an accurate and stable extrusion process.

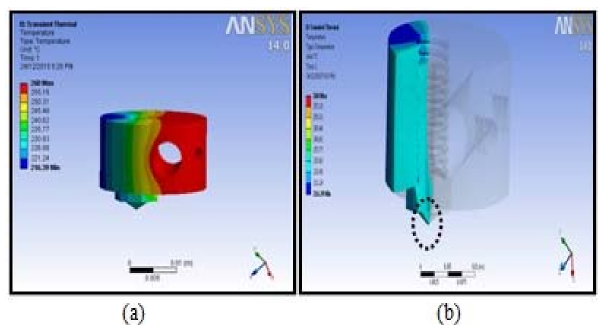
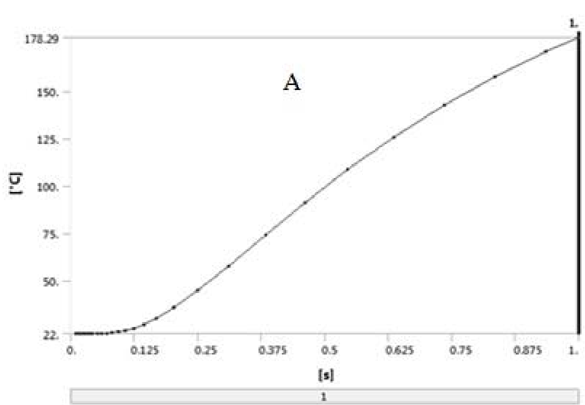


Figure-8(a). Cylindrical liquefier design and **Figure-8(b).** Temperature at the nozzle tip around 226.08 °C (499.23K).

The plot in Figure-9 shows the heat transfer rate for the square shape and the cylindrical shape at 1 s. For the cylindrical shape, the temperature distribution can reach 216.39 °C (489.54K) in 1 s in comparison with the square shape, for which a temperature of only approximately 178.29 °C (451.44K) is reached, showing a difference of approximately 38.10 °C (311.25K).



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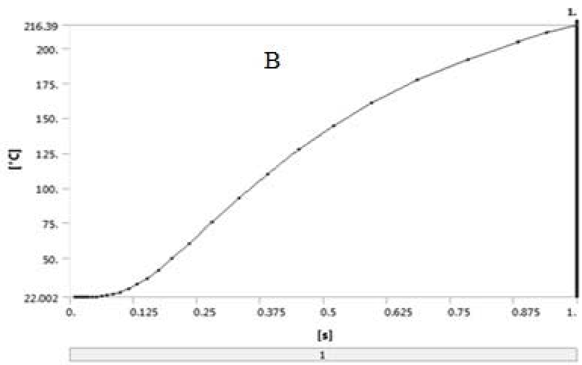

Figure-9. Comparison of the temperature distribution at 1 s for square (A) and cylindrical (B) shapes.

Flow behavior along the liquefier

The simulation results for original liquefier design indicate that the temperature at the nozzle tip before the filament is inside is approximately 196.45 °C (469.6K). Because the melting point of the PLA material is approximately 160 °C (433.15K), it is crucial to maintain the temperature that is equal to or lower than the melting point. As shown in Figure-10, the temperature in the red zone before leaving the nozzle is 187.85 °C (461K), which is much higher than the melting point of PLA and far from the optimum temperature conditions. Temperatures that are much higher than the optimal temperature cause the material to burn and temperatures that are much lower than the melting point of the material can cause the unwanted bonding between the deposited layers. This phenomena happened because of improper setting printing temperature on the interface. Therefore, the input temperature of the system can be adjusted to obtain the optimum temperature for PLA, which is equal to or slightly lower than 160 °C (433.15K).

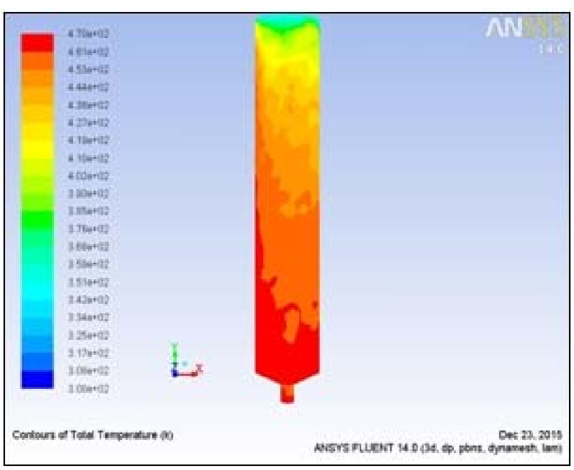

Figure-10. Heat transfer from the liquefier wall to the material through the outlet nozzle.

The melt flow behavior inside the liquefier can be simulated for the new design. To determine the optimal temperature setting for the system for the extrusion of the PLA material, the temperature distribution inside the liquefier is shown in Figure-11 using the Capped IsoSurfaces option. The temperature setting for this system is 190 °C (463.15K), as detected by the thermocouple. Along the liquefier, the temperature is approximately 168.02 °C (441.17K); this value can be used to set the wall temperature and the outlet temperature in the flow simulation. The same method has been used to observe the flow behavior of the PLA material in the liquefier.

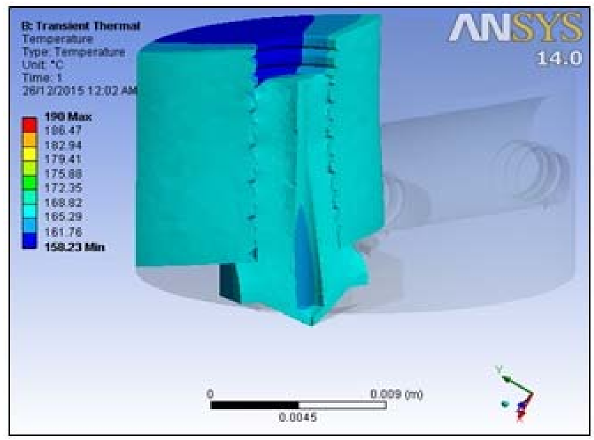

Figure-11. Temperature at the nozzle tip for 190 °C (463.15K) input setting for cylindrical shape.

Examination of the temperature distribution along the liquefier presented in Figure-12 shows that the material reaches the 168.02 °C of printing temperature in the orange zone before leaving the nozzle. Considering heat loss by convection, it is acceptable that the temperature of the material leaving the nozzle in the simulation is slightly higher than the melting point temperature of approximately 165 °C (438.15K). Sufficient space is available for the material to evenly and completely melt before leaving the nozzle at the optimum extrusion temperature. Based on the simulation, the temperature setting for the system for extruding the PLA material using open-source 3D printing is 190 °C (463.15K).

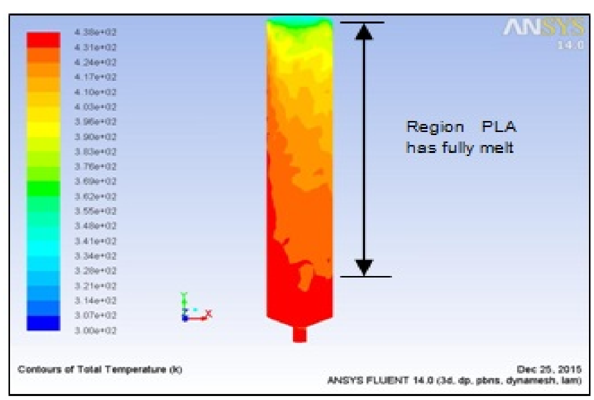

Figure-12. Heat transfer from the liquefier wall to the material at wall temperature 168.02 °C (441.17K).

CONCLUSIONS

Temperature distribution along the liquefier has been observed for the original liquefier design as well as for the proposed cylindrical design, and the simulation results show that the cylindrical shape is a better design for obtaining an enhanced heat transfer rate that can minimize the effect of the time delay during the adjustment of temperature in the system. For a successful extrusion process, the printing temperature for the PLA material must be set at the optimum temperature. FEA simulation has been performed, and the printing temperature suggested for the extrusion of the PLA material using open-source 3D printing is 190 °C (463.15K).

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