Heat Distribution of Aluminum Block with Profile for Portable Thermal Cycler Calculated Using Finite Element Method

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Abstract. Polymerase Chain Reaction (PCR) becomes one of the essential tools during the COVID pandemic. The heart of the PCR is a thermal cycler. The thermal cycler is a temperature cycle instrument that changes and maintains the vial sample's temperature at a specific target temperature. A simple thermal cycler can be made using thermoelectric as the heater and cooler to control the temperature state. The thermal block temperature distribution is important to make all the vials treated at the same temperature condition. The thermal distribution of an aluminum block as the thermal block for a portable PCR was calculated using the finite element method. The heat source and cooler with a power of 60W were placed at the bottom of the aluminum block. The temperature gradient inside the aluminum body, where the vial was placed, was calculated. The heating and cooling speed were calculated using the model. It was found that the temperature difference between the bottom surface and top surface of the aluminum block is 2.5°C during the transient time. The temperature distribution in a horizontal direction is homogenous, with a temperature difference among the surface being less than 0.01°C. The time required to heating from 24°C to 95°C is 31.05 seconds while cooling from 95°C to 55°C can be reached in 18.05 seconds.

1. Introduction

The thermal cycler is the heart of the polymerase chain reaction (PCR) system. The system consists of a heat source, cooler, thermal block, and electronic control. The heat was distributed to the vial tube sample through a thermal block connected to the heat source and cooler. Temperature ramp speed is one form many important factors for a good thermal cycler. The sample placement and thermal block materials are important to get high ramp speed [1]. The thermal block is made of silver for higher heat transfer or coated gold or coated silver. However, and a low-cost thermal cycler aluminum block is usually used. According to the technical data, several PCR thermal cyclers in the market have a ramp rate from 3°C/s to 10°C/s. However, a low-cost thermal cycler has a temperature ramp of 1°C. The temperature ramp speed depends not only on the thermal block but also on the heat source.

Thermal distribution is a critical aspect of PCR [2]. Also, the temperature ramp is important to achieve a shorter cycling time. Microtubes, to minimize the thermal capacity, was developed [3] for fast thermal cycling. The PCR reaction chamber's temperature distribution showed a gradient temperature in the chamber surface during the heating process [4]. Temperature differences in the chamber should be maintained low to make biochemical reactions during the DNA replication works.

A computational fluid dynamic (CFD) model using ANSYS was used to simulate a heat transfer and thermal distribution of various heaters [5]. The CFD was also used to simulate thermoelectric...
element cooler TEC in cooling [6]. Other thermal analyses using ANSYS can be found in many papers [5,7].

A numerical calculation of temperature distribution for a small aluminum block for PCR was done in this work. Temperature distribution in the vertical and horizontal directions in the aluminum block and the aluminum surface was investigated.

2. Simulation Method and Setting

Based on the thermal block design, aluminum's temperature distribution was calculated using finite element software (ANSYS). The system aluminum block design is presented in Figure 1. The dimension of the aluminum is 30mm × 30mm × 15mm. The aluminum material is Al 7075. The physical properties of Al 7075 are listed in Table 1. The aluminum thermal block hole is a cone shape with a diameter of 5mm and a depth of 10mm.

The thermal block heating process was carried out by providing heat flow to raise the temperature from 24°C (room temperature) to 95°C. A heat source was given to the bottom of the thermal block with a power of 60W. When the temperature reached 95°C, the thermal block will be cooled to a temperature of 55°C. The cooling process was done by changing the heat source with a 60W cooler at the bottom of the thermal block.

![Figure 1. The aluminum thermal block model](image)

Table 1. Aluminum property used in the simulation

| Property                          | Value  |
|----------------------------------|--------|
| Density (kg/m3)                  | 2810   |
| Isotropic thermal conductivity   | 196    |
| (W/mK)                           |        |
| Specific Heat (J/KgK)            | 714.8  |
| Young's Modulus (GPa)            | 71.7   |
| Poisson's Ratio                  | 0.33   |

In this simulation, the Transient Thermal Analysis solver, which is available in ANSYS, was used. In the case of transient thermal, the system temperature will change over time. The process of conserving thermal energy used is described in the first law of thermodynamics. The internal energy of the system will increase when heat flows into the system and vice versa. The temperature change due to heat flow in the conduction process can be calculated by Equation 1.

\[
k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q = \rho c \frac{\partial T}{\partial t}
\]

Where:
\( k \) = Thermal conductivity \((W/K \cdot m)\)
\( \rho \) = Density \((kg/m^3)\)
\( c \) = Specific heat \((J/kg \cdot K)\)
\( T \) = Temperature \((K)\)
\( t \) = Time
\( q \) = Heat

The meshing method used is a tetrahedron with an accuracy of 0.2 mm and refinement in certain areas. This meshing method produces a mesh with 813068 nodes and 499946 elements. The mesh on the system can be seen in Figure 2.

**Figure 2. Mesh of the aluminum block in ANSYS Workbench**

3. Result and Discussion

The aluminum block's temperature data was taken after the aluminum block's surface temperature reached the target temperature. The body temperature of the block, surface temperature, and temperature inside the aluminum block was taken.

Figure 3a shows the aluminum block's body temperature distribution at the target surface temperature of 95°C. The surface temperature reached 95.033°C from an initial temperature of 24°C within 31.05 seconds. We can see that the temperature at the bottom, where the heat source was placed, 2.5°C higher than the top surface temperature. Figure 3b shows the aluminum block's body temperature during the cooling process to a target temperature of 55°C. To change the top surface temperature from 95°C to 55°C required 18.05 seconds. The temperature ramp speed is around 2°C/s. This temperature ramp speed is slower than the claimed temperature ramp speed but closed to a practical operation ramp speed [8].

**Figure 3. The body temperature distribution of aluminum block (a) heating to 95°C (b) cooling to 55°C.**
Inside the aluminum block, the cross section's temperature profile at the cone position is presented in Figure 4a, and the heating process was done with a target surface temperature of 95°C. The temperature difference from the top surface to the bottom surface is 2.519°C. As the heat source was given from the bottom, the higher temperature at the bottom surface is the consequence. Figure 4b shows the temperature gradient at the same position after cooled from 95°C to 55°C. The temperature difference between the top surface and bottom surface is 2.518°C. The top surface has a higher temperature than the bottom surface. The temperature difference is well understood as the heat was removed only from the bottom surface. Temperature gradient and temperature difference in the vertical direction is the consequence of the temperature change, which is calculated using equation 1.

The detailed temperature gradient in the vertical direction during the heating and cooling is presented in Figure 5. The temperature profile in the vertical direction is asymptotic to the target surface temperature. The curves form a second-order differential equation solution of equation 1. The temperature difference from the bottom of the cones to the top surface is around 1.5°C. It is better than the 3°C temperature difference reported [4].

![Figure 4. Aluminum block vertical cross-section temperature distribution (a) heating to 95°C (b) cooling to 55°C.](image)

![Figure 5. Aluminum block temperature profile in the vertical direction (a) heating to 95°C (b) cooling to 55°C.](image)

The surface temperature distribution of the aluminum block is presented in Figure 6. In the horizontal direction, there is no significant temperature difference in the aluminum block. The temperature difference is only 0.01°C at targeted surface temperature of 95°C and 0.007°C at the
targeted surface temperature of 55°C. The simulation's temperature distribution is better than the reported microchannel heat distribution, which was more than 1°C [9]. At heating to 95°C, the temperature in the tube wall and the air are highest during heating (95.04°C) and lowest during cooling (54.972°C).

![Figure 6. Surface temperature distribution (a) heating to 95°C (b) cooling to 55°C.](image)

4. Conclusion

Temperature distribution of aluminum thermal block, which is intended for thermal cycler heating cooling block, has been simulated using FEM. The simulation showed that the temperature distribution on the surface in the horizontal direction is equal. The temperature difference in the horizontal direction is 0.01°C or less. In the vertical direction, the temperature difference at the heat source or cooler side to the block surface is 2.5°C. The temperature ramp-up speed is 2°C/s.

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**References**

[1] Burroughs N and Karteris E 2013 Ultra-High-Speed PCR Instrument Development *PCR Technology* (CRC Press) pp 143–58
[2] Hsieh T M, Luo C H, Huang F C, Wang J H, Chien L J and Lee G Bin 2008 Enhancement of thermal uniformity for a microthermal cycler and its application for polymerase chain reaction *Sensors Actuators, B Chem.* 130 848–56
[3] Poser S, Schulz T, Dillner U, Baier V, Köhler J M, Schimkat D, Mayer G and Siebert A 1997 Chip elements for fast thermocycling *Sensors Actuators, A Phys.* 62 672–5
[4] Chen J J, Li K T, Chen W H and Yang Y T 2014 Analysis of thermal performance in a bidirectional thermocycler by including thermal contact characteristics *Micromachines* 5 1445–68
[5] Reddy Kummitha O and Reddy B V R 2017 Thermal Analysis of cylinder block with fins for different materials using ANSYS *Mater. Today Proc.* 4 8142–8
[6] Rednic V, Guttr R, Bruj E and Bot A 2021 Two-stage heat recovery system equipped with thermoelectric elements *Appl. Therm. Eng.* 185 116412
[7] Imran M, Zhang L and Gain A K 2020 Advanced thermal metamaterial design for temperature control at the cloaked region *Sci. Rep.* 10 1–11
[8] Chen R, Lu X, Li M, Chen G, Deng Y, Du F, Dong J, Huang X, Cui X and Tang Z 2019 Polymerase chain reaction using "V" shape thermal cycling program *Theranostics* 9 1572–9
[9] Miralles V, Huerre A, Malloggi F and Jullien M-C 2013 *A Review of Heating and Temperature Control in Microfluidic Systems: Techniques and Applications* vol 3