Two-Dimensional Finite Element Simulation of Micro-Electric Discharge Machining of Ti-6Al-4 V

B. C. Karthik, P. K. Pradeesh Karun, P. Sanal, Ch. Surendra, and Basil Kuriachen

1 Introduction

Machining process is one among the most prominent processes spreads widely in the whole domain of mechanical and manufacturing engineering. Technological advancements emerging day by day enhance the efficiency of processes being conducted and make processes further simpler. Miniaturization is a significant trend coming into the present technological level of manufacturing. Manufacturing micro-sized machine parts and components have got a great application in the various industries which includes the fabrication of micro-holes and other micro-level features in turbine blades, fuel injection nozzles, optical products, hydro-pneumatic valves, etc., that require higher amount of precision and accuracy.

Micro-electrical discharge machining is an important non-traditional machining process which exerts negligible residual stress due to its non-contact nature. It also enables to produce a lot of geometrically complex micro-features in electrically conductive solid materials with high accuracy irrespective of their hardness. So EDM

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is one of the main techniques used for manufacturing complex-shaped dies, components for surgical, aerospace and other precision engineering industries [1]. It utilities electrical discharges (sparks) for obtaining required machined surface. Removal of workpiece material takes place by a series of discharge pulses between two electrodes separated by dielectric fluid on applying a voltage.

From a source, the sparks are made to discharge at high frequency in which a suitable spark gap is maintained between tool and workpiece that can be adjusted with the help of a servo motor. The main advantage of EDM is that a uniform MRR is obtained as the closest distance at each spot changes after each spark. When suitable voltage is built up, emission of electrons from cathode to anode takes place which collides with the atoms of dielectric molecules to split up and produce more ions and electrons. A conductivity channel is established as these electrons and positive ions move towards anode and cathode, respectively. This causes high temperature, melting and vaporizing of both the tool electrode as well as workpiece. But due to the impact produced by positive ions on cathode is much smaller than caused by electrodes on anode, tool wear is comparatively less as that of workpiece wear. In addition, a thin carbon film produced from pyrolysis of dielectric fluid creates a protective layer on tool.

It is very difficult to study and experimentally observes the exact theory of mechanism behind the EDM process which can exactly predict the amount of material removal during EDM machining because of its complexity [2]. So modelling of EDM process can help to understand the comprehensive view of the process which includes the temperature distribution in the workpiece material due to the effect of discharge pulses. Finite element model is accurate and powerful technique to model any complex shapes by applying necessary boundary conditions, and in this work, the finite element analysis is coded in MATLAB software. FEM can help in providing a good approximation of the material removed in the machining process. This can help in suitably choose parameters for process in the machining. It will also aid in predicting the rate of material removal as well as tool wear ratio.

This paper studies a model based on the electro-thermal theory to find out the geometry of crater formed from single discharge pulse. The developed model is able to anticipate the temperature distribution using the average voltage and current values obtained from voltage and current probes during the material removal process. By solving this thermal problem, the temperature distribution inside the workpiece from which the shape as well as the radius and depth of the generated craters can be estimated by comparing the temperature value at each node with the melting temperature of the material. The material removal rate can be found by means of both radius and depth of the crater. Further, an algorithm for tool wear compensation can be developed by real-time monitoring of the material removal rate and comparison with target volume to be removed. So online monitoring of EDM process can help get optimum machining conditions thereby achieving higher machining efficiency and performance [3]. Temperature distribution is one of the main factors affecting the material removal in electric discharge machining. Hence, it is given importance in this particular study of EDM. Various parameters of thermal process were considered while developing the model. It comprises various heat transfer modes that includes conduction and convection, latent heat associated with the material melting and evaporating, the efficiency of heat transfer to the workpiece material, the radius of spark and electrode and thermal properties of workpiece material. In addition, Gaussian heat flux was considered for applying the heat flux boundary condition on to the developed model. Moreover in case of implementing online tool monitoring system for tool wear compensation, the developed FEM model can be used to predict the material removed based upon the voltage and current values obtained so that the machining need not be stopped in between for getting the measured value of crater dimensions. This helps in obtained the crater volume which can be compared with target volume to get the required tool compensation length.

Yeo et al. developed an analytical model to estimate the dimensions of the crater which showed that the theoretical and experimental results are found to be very close [4]. Nadda et al. proposed that the finite element simulation can be used to determine the crater dimensions created by a spark discharge [5]. The value of crater depth and crater radius varies according to the voltage and current of the machining. Here they found that the crater size obtained by finite element simulation is very close to the experimentally obtained values. Kuriachen et al. showed that thermal analysis of single spark model gives the results that are very close to experimental results [6]. This utilized the Gaussian distribution of heat flux for performing the transient thermal analysis and predicted the crater geometry for different voltage and capacitance. Xie et al. proposed a model to predict the crater geometry of EDM by considering that the energy dissipated to the workpiece will be only a part of the total energy of the spark discharge [7]. Rajeev Kumar and Vinod Yadava presented a thermal model to analyse the temperature distribution in the zone of influence of micro-EDM spark discharges and determined the crater radius and crater depth by using the melting isotherm curve at various energy levels [8]. It predicted how the energy partition influencing the crater dimension. Nadda et al. proposed that the energy of each discharge pulse and the corresponding volume of material removed is a variable that depending up on the electrical parameters [9]. Marafona and Chousal proposed an electro-thermal model by using Joule heating factor, and it assumes the discharge channel as a heat dissipating electrical conductor where the conductor radius is a function of intensity of current and pulse duration. Zhang et al. inferred that expansion of the plasma diameter must be taken into consideration in order to be more consistent with the actual EDM process. Also, the power density was an important factor that affects the material removal and energy efficiency. With short pulse duration, the material removal and energy efficiency were much higher due to the higher power density [10]. Jamwal et al. concluded that in EDM, electrical parameters like voltage peak current, pulse on time, pulse off time, etc., affect the quality of surface produced. In addition, non-electrical parameters like dielectric flushing, rotation of tool and workpiece, proper addition of additive in dielectric, etc., also have a role in obtaining optimum performance of EDM [11]. Jithin et al. observed that with rising values of discharge current and pulse on time, crater depth and radius increases. It was because of increased duration of input heat flux and input pulse energy. In addition to it, the aspect ratio has a high value at low values of current and pulse on time due to less penetration of heat into workpiece at lower parameter values [12]. Zhang et al. developed a parameterized Gaussian heat flux model to obtain the optimal Gaussian heat flux distribution. The results were validated by comparing with the experimental single discharge results to find the optimal heat flux distribution [13]. Zhang et al. concluded that volume wear increases with the increase of current, voltage and pulse width. Moreover, the simulation can tell about the material removal rate with less error rate [14]. Jain mentions that unlike in EDM, the damage due to heat-affected zone in micro-EDM is very much less because of the low energy sparks in micro-EDM [15].

2 Electro-thermal Modelling of a Single Discharge Pulse

The single discharge pulse can be modelled by defining a suitable computational domain, providing necessary governing equation and applying appropriate initial and boundary conditions.

2.1 Assumptions

1. The heat flux distribution over the top edge of the domain is a Gaussian distribution.
2. Flushing efficiency is 100%, i.e. flushed workpiece particles will not deposit on the workpiece again.
3. The radiative heat transfer from the workpiece is neglected.
4. Electro-thermal model of a single spark is considered to study.
5. Negligible heat transfer on the left, right and bottom edges.
6. Transient analysis is to be conducted.
7. Eight percentage of the total heat flux is used up for the material removal from workpiece.
8. The material is homogenous and isotropic in nature.

2.2 Computational Domain

The computational domain taken for the simulation of a single discharge pulse crater involves a cross-sectional rectangular plane with one of the top corners at centre of the plasma channel centre, as shown in Fig. 1.

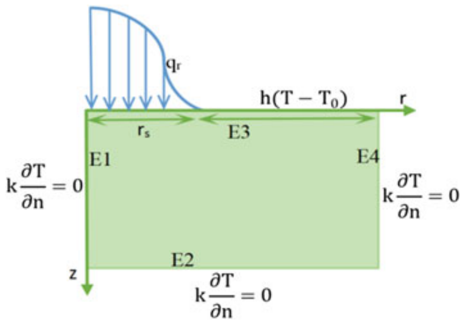

Fig. 1 Schematic diagram of the axisymmetric domain with boundary conditions

2.3 Governing Equation

With regards to all assumptions for the single discharge model, the partial differential equation taken as the governing equation is:

$$\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where *T(x, y)* is the temperature distribution across the domain and α is thermal diffusivity.

The thermal diffusivity can be calculated as:

$$\alpha = \frac{k}{\rho c_p} \tag{2}$$

where ρ is the density of workpiece material.

Here the thermal conductivity, k, and specific heat, c_p, are both considered as temperature dependent functions.

2.4 Initial Condition

Before the application of the heat source, we assume the temperature of the domain (workpiece) to be constant and equal to the room temperature T_a, i.e.

$$T(r, z, t = 0) = T_a \tag{3}$$

2.5 Boundary Conditions

We assume that the convective heat transfer between edges $E1$, $E2$ and $E4$ is negligible, making the heat flux equal to zero, i.e.

$$\frac{\partial T}{\partial n} = 0 \tag{4}$$

where n is a unit vector normal to the surface of the domain.

For edge $E3$, the heat flux due to the spark, q_r, acts within the spark radius r_s. Beyond r_s, convective heat transfer takes place due to the application of dielectric fluid, with heat transfer coefficient taken as 1000 W/m^{2}K.

$$-k(T)\frac{\partial T}{\partial y} = \begin{cases} q_{\mathrm{r}} & \text{if } r < r_s \\ h(T - T_a) & \text{if } r > r_s \end{cases} \tag{5}$$

where T_a is the ambient temperature, taken as 298 K.

2.6 Formulation of Heat Flux

By assuming Gaussian heat distribution, the heat flux can be written as:

$$q_r = q_0 e^{-3\left(\frac{r}{r_s}\right)^2} \tag{6}$$

where the maximum heat flux, $q_o = 3.157q$, and q is the uniform heat flux density rate [16].

The spatial distribution of heat flux density rate is given by:

$$q = \frac{Q_a}{\pi r_s^2} \tag{7}$$

where Q_a is the available heat flux.

The ratio of available heat flux to total heat flux, η, can be taken as 8% [17]. Therefore,

$$\eta = \frac{Q_a}{Q} = 0.08 \tag{8}$$

The total heat flux can be calculated as:

$$Q = \frac{E_d}{T_{\mathrm{On}}} \quad (9)$$

where E_d is the energy dissipated by the capacitor and T_{on} is the pulse on time of the voltage pulse [18].

The energy stored in the capacitor is formulated as:

$$E_d = \frac{1}{2} C_d V_d^2 \quad (10)$$

where C_d and V_d are respective capacitance and voltage of the RC relaxation circuit that produces the pulse for the micro-EDM.

Using power regression, the equation for spark radius, r_s, is found to be [19]:

$$\begin{aligned} r_s &= 21.47 + (0.0026 * C) - (0.046 * V) \\ &\quad + \left(1.47 * 10^{-4} * C * V\right) - \left(1.27 * 10^{-5} * C^2\right) \end{aligned} \quad (11)$$

2.7 Consideration of Latent Heat of Fusion

During the micro-electric discharge machining, a part of the heat is utilized for the phase change of the workpiece material from solid to liquid state. An apparent specific heat can be used for incorporating the effect of latent heat with the specific heat value. Therefore, apparent heat capacity can be defined as,

$$c'_p = c_p + \frac{L_f}{\Delta T_M} \quad (12)$$

where c_p is the specific heat capacity.

L_f is the latent heat of fusion.

ΔT_M is the difference between solidus and liquidus temperature.

3 Finite Element Analysis

For conducting, the transient axisymmetric thermal analysis for a single pulse discharge in micro-electric discharge machining, Partial Differential Equation Toolbox available in MATLAB is used for modelling and solving the problem. The steps in thermal analysis of single pulse discharge on MATLAB are as follows:

Table 1 Process parameters for the micro-EDM

Process parameter	Type/Value
Type of analysis	Two-dimensional transient thermal analysis
Convective heat transfer coefficient (h)	1000 W/m^2K
Work material	Ti-6Al-4 V
Initial temperature	25 °C
Spark on time (T_{on})	3 μs
Voltages	80 V, 115 V, 150 V
Capacitances	1.1μF, 2.2μF

3.1 Pre-processing

i. Define a thermal model as an axisymmetric steady state analytical model.
ii. Open the PDE Modeler app in MATLAB to create a geometry and name the geometry description, set formula and name space matrices.
iii. Add the geometry with the thermal model defined, using the geometryFromEdges() function in the PDE Toolbox.
iv. Add the thermal properties of the workpiece such as heat transfer coefficient and specific heat capacity as given in Table 1 with the model.
v. Generate a mesh grid in the domain with appropriate element size.

Use the thermalBC() function to define the boundary conditions for edges E1, E2 and E4 as zero heat flux. Then define the boundary conditions in edge E3 as given in Eq. 1.

vi. Use the thermalIC() function to define the initial condition as $T(t = 0) = 0$.

3.2 Solution

Using solve() function, the thermal model can be solved and the result is stored.

3.3 Post Processing

i. Plot the temperature in the result to get the temperature distribution contour.
ii. Find the value of rand z for which the temperature on the domain becomes equal to melting point of the workpiece, in order to find the crater radius and crater depth, respectively.

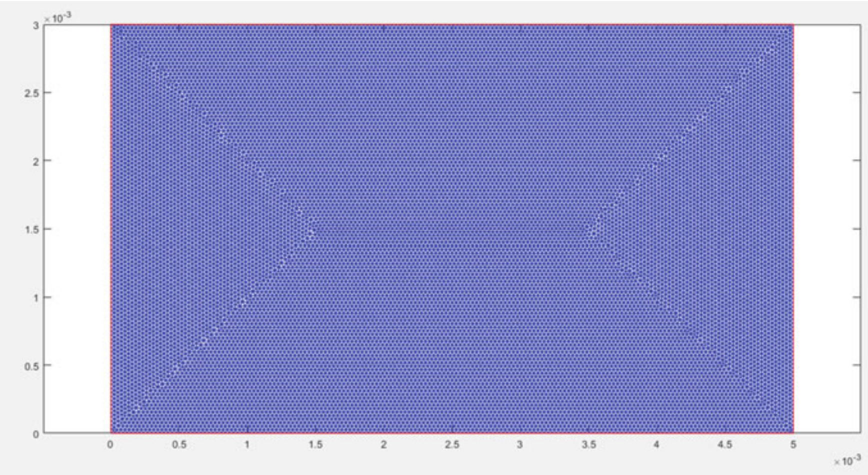

Fig. 2 2D meshed grid

4 Results

The temperature distributions are shown in Figs. 3, 4, 5 and 6. The temperature is maximum at the left top corner, and it decreases along the r and z axes. Since, the input parameters that are in our control are voltage and capacitance, it is important to analyse the variation of temperature with these parameters. In order to find the relation between capacitance and temperature of the workpiece, maximum temperature in the resultant temperature distribution is found for various values of capacitance (1.1 and 2.2μF), while keeping the voltage constant at 80 V (Figs. 3 and 4). It was found that the maximum temperature increases with increase in capacitance of the RC relaxation circuit. This can be reasoned that, with increase in capacitance, the energy stored in the capacitor increases according to Eq. 9. The discharge of the capacitor causes the increase in the available heat flux, which causes an increase in the temperature.

For checking the changes in temperature with change in voltage, three values of voltage are considered (80, 115 and 150 V), at a constant capacitance of 1.1μF. It also shows an increase in temperature with increase in voltage, due to the increase in the energy stored in the 1μF capacitor (Figs. 4, 5 and 6).

Possible error that can raise in the solution is that flushing efficiency is assumed to be 100%, which means that deposition of the removed particles will not occur. In reality, the efficiency is less than 100%, which can cause a decrease in the crater size and radius than expected.

It can be seen from the graphs for temperature along R and Z axes that temperature reduces through the axis more quickly for Z axis than along R axis. This is because of the presence of direct heat source acting along the radial axis which increases the temperature along r axis (Figs. 7 and 8).

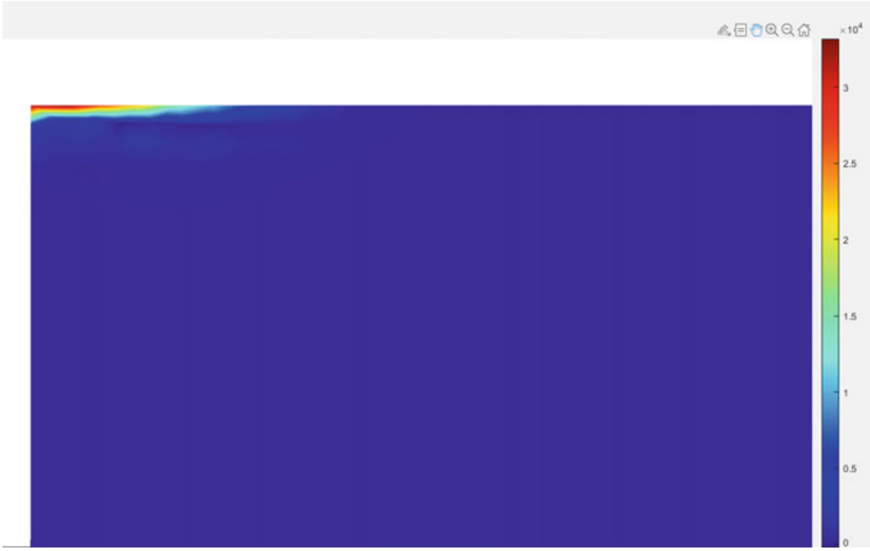

Fig. 3 Zoomed view of temperature distribution for $V = 80$ V and $C = 2.2\mu$F

Fig. 4 Zoomed view of temperature distribution for $V = 80$ V and $C = 1.1\mu$F

5 Conclusion

On completion of the transient thermal analysis of the electro-thermal model of the single discharge pulse in micro-electric discharge machining, it can be inferred that:

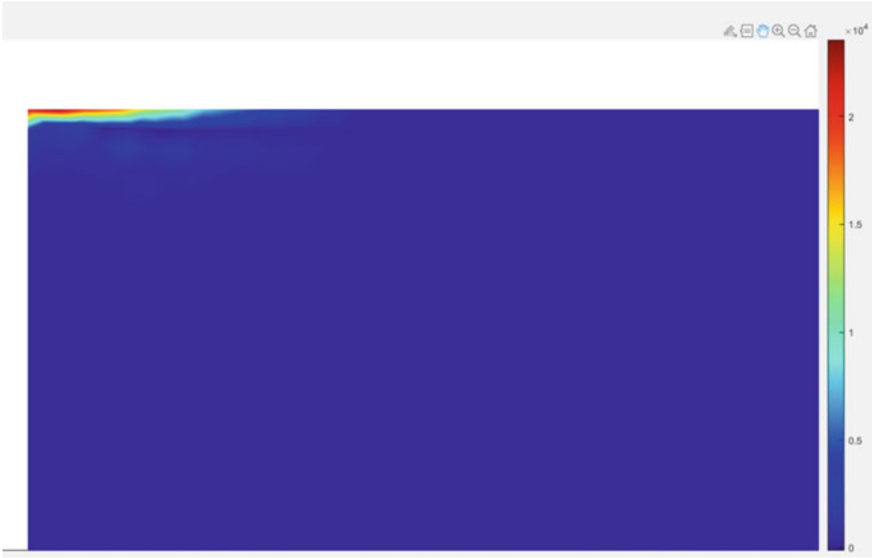

Fig. 5 Zoomed view of temperature distribution for $V = 115$ V and $C = 1.1\mu$F

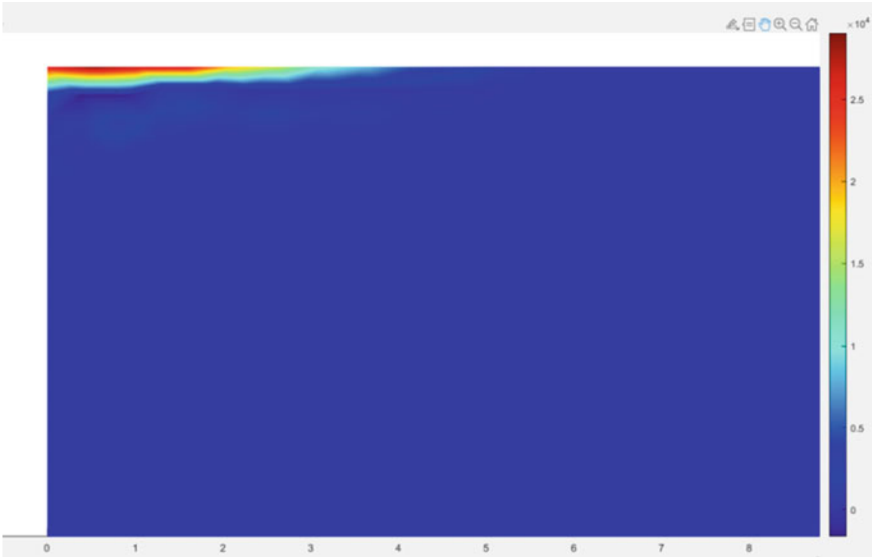

Fig. 6 Zoomed view of temperature distribution for $V = 150$ V and $C = 1.1\mu$F

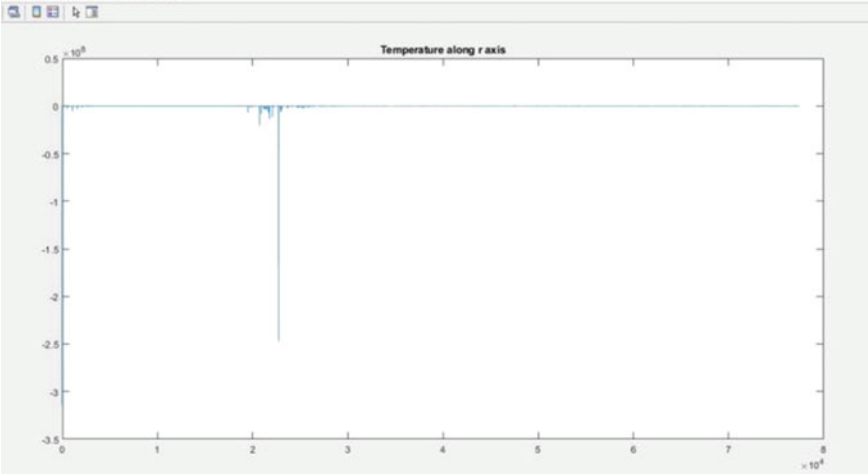

Fig. 7 Temperature variation along radial axis for $V = 80$ V and $C = 0.01\mu$F

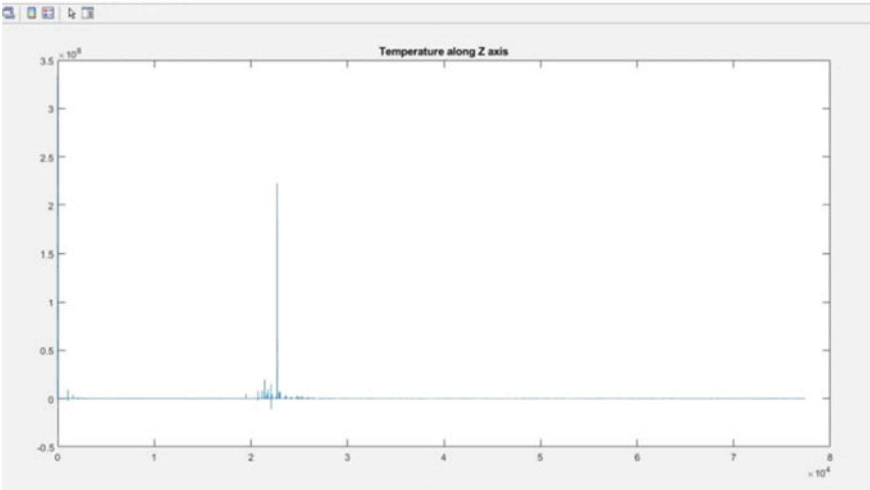

Fig. 8 Temperature variation along Z axis for $V = 80$ V and $C = 0.01\mu$F

i. The result obtained after solving the finite element problem closely check with the existing numerical simulations and studies regarding micro-EDM.
ii. Increase in capacitance and voltage can increase the maximum temperature in the resultant temperature distribution.
iii. In continuation with this analysis, an algorithm to compensate the real-time tool wear in micro-EDM is under development, along with the help of a suitable pulse discrimination strategy.

iv. Due to the presence of heat flux on the radial axis, the temperature varies quickly along the z axis than that along radial axis.

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