A comparative investigation on temperature distribution in electric discharge machining process through analytical, numerical and experimental methods

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ABSTRACT
Electric discharge machining (EDM) is a widely-used non-traditional machining process in manufacturing of complicated structures based on localized thermal loads. Because of numerous difficulties in measuring temperature, no adequate knowledge on temperature distribution of workpiece, tool and plasma channel is available. On one hand, a large number of dispersedly-published papers have been reported so far to model the temperature distribution either analytically or numerically. On the other hand, an enormous amount of experimental attempt has been put into measuring the temperature by directly-measuring methods. In this study, a comprehensive review of analytical, numerical and experimental investigations on temperature prediction has been provided to organize different methods to integrate them as useful information for elucidating the differences between approaches and identifying their proximities to the real temperature distribution. This review also prepares a classification of the different methods of investigating temperature and provides an overview of some of the recent advances in this area to help researchers on selecting appropriate approaches among analytical, numerical and experimental techniques depends on applications and the availabilities of those techniques. The assumptions, limitations and features of different methods are described. Finally, the paper shows some required enhancements for EDM process to improve the total accuracy of temperature prediction as well as recommendations for future studies.

1. Introduction

Electric discharge machining (EDM) is a widely-used material removal technique based upon the concept of material removal from electrical conductive components by erosive effect of highly concentrated heating sources. Short duration discharges generated in a liquid dielectric gap separating the tool and workpiece, can make a melted zone on the surface of workpiece. The main cause for material removal from both of the electrodes in EDM process is the temperature above the melting points. This temperature is due to the excessive thermal energy, which is generated in the discharge channel.

This process has emerged in the 1940s, in which a vast variety of products such as dies and molds which can be produced by EDM process [1]. Finishing the surfaces of automotive industry and surgical components can be easily performed by EDM. Since there is no need to contact mechanically between tool and workpiece, this machining method has been continuously evolving from a mere tool and die making process to Micro/Nano scale manufacturing applications [2,3]. It is due to the unprecedented potential of an extensive demand for familiar size parts with tiny added features of high precision and to attract a vast variety of research interests in the field of EDM [4]. Recently, EDM has been also adapted for nanofabrication process as a popular technique in the machining industry [5], and production of dental alloys [6–8].

As EDM process has no direct contact between the electrode and the work piece, it can also prevent undesired problems such as mechanical stresses, chatter, vibration, etc. during machining. Other advantages of this method are namely the convenient shaping of complicated geometries and the possibility of machining of either super hard materials or fragile pieces for which conventional techniques cannot handle. Materials with any level of hardness can be easily machined as long as the material can conduct electricity. Also, combining EDM process with other machining processes can lead to the great results such as high quality, high efficiency, high productivity

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Nomenclature

\[
\begin{align*}
T & \text{ temperature (K)} \\
r & \text{ radial axis (m)} \\
z & \text{ vertical axis (m)} \\
t & \text{ time (s)} \\
K_t & \text{ thermal conductivity (J/mK s)} \\
C_p & \text{ specific heat (J/kg K)} \\
C_{pm} & \text{ specific heat in melting state (J/kg K)} \\
C_{pr} & \text{ specific heat in evaporation state (J/kg K)} \\
m & \text{ latent heat of melting (kJ/kg)} \\
T_m & \text{ melting temperature (K)} \\
P & \text{ energy intensity} \\
q & \text{ heat flux (W/m2)} \\
F_i & \text{ fraction of total energy (%) } \\
V & \text{ voltage of discharge (V)} \\
I & \text{ current of discharge (Amp)} \\
r_p & \text{ radius of the heat source (m)} \\
P_{\text{plasma}} & \text{ plasma channel radius (\(\mu\)m)} \\
q_{\text{th}} & \text{ maximum heat flux (W/m2)} \\
\mu & \text{ on-time pulse (\(\mu\)s)} \\
R_{\text{plasm}} & \text{ plasma channel radius (\(\mu\)m)} \\
Q_p & \text{ energy fraction of workpiece} \\
P_f & \text{ ambient pressure (bar)} \\
P & \text{ plasma pressure (bar)} \\
R_f & \text{ ill-defined constant (mm)} \\
K & \text{ experimental constant} \\
m & \text{ experimental constant} \\
n & \text{ experimental constant} \\
r_p & \text{ plasma channel radius (\(\mu\)m)} \\
T_0 & \text{ ambient temperature (K)} \\
\text{erf} & \text{ error function} \\
r_0 & \text{ radius of outer area of cathode (m)} \\
L & \text{ height of cylinder (m)} \\
P_0 & \text{ effective power of energy source} \\
X & \text{ and Y coordinates} \\
L_m & \text{ latent heat due to melting} \\
L_e & \text{ latent heat due to evaporation} \\
\alpha & \text{ thermal diffusivity formulation (m\(^2\)/s)} \\
\lambda & \text{ dummy integration variable} \\
\theta & \text{ dimensionless temperature} \\
\epsilon & \text{ perturbation parameter} \\
\rho & \text{ material density (kg/m\(^3\))} \\
\rho_v & \text{ constant liquid density (kg/m\(^3\))} \\
v_r & \text{ radial velocity (mm/s)} \\
\end{align*}
\]

Greek symbols

\[
\begin{align*}
a & \text{ thermal diffusivity formulation (m\(^2\)/s)} \\
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v_r & \text{ radial velocity (mm/s)} \\
\end{align*}
\]

Subscripts

\[
\begin{align*}
i, j & \text{ k itination time in direction x, y and z} \\
\end{align*}
\]

and low geometrical errors [9]. For instance, EDM process can be combined effectively with other machining process, like Electro Chemical Machining (ECM) to enhance the efficiency of material removal [10,11].

In EDM process, a combination of several various disciplines such as thermodynamic, electrodynamics, hydrodynamic, and electromagnetic phenomena are involved making it difficult to express the process in a simple and comprehensive model in terms of process parameters. As the control of basic process parameters can influence temperature distribution and consequently affect different aspects of process such as surface quality, micro-crack, tensile residual stress [12], surface roughness, and also the global optimization of the process [13], it is important that many experimental studies involving the temperature investigating are conducted to check the validity of the various already proposed models. Moreover, the temperatures of the workpiece and tools play a major role in developing the modeling of critical characteristics of EDM process based on predicted temperature. However, experimental temperature measurement techniques have been so far developed in many areas with the aim of validating proposed either numerical or analytical models.

Because the different proposed models of temperature prediction as functions of controllable process variables are considerably numerous, a continual need for a comprehensive review of various experimental, numerical and analytical models for EDM processes is being felt. This paper intends to fulfill this need in the area of EDM to not only distinguish the advantages, disadvantages and assumptions of each approach but also specify the technical prerequisites for experiments and unavoidable limitations. Various analytical and some semi-empirical/empirical temperature prediction models are exhaustively reviewed to be presented in a suitable guide for quick reference for those who intend to research temperature distribution prediction. In other word, the data gathered in this review paper, can be further used in the existing thermo-physical models, expecting for researchers to choose the best method and bring their models precisely more close to actual practices. This paper has been organized as follows: Section 2 comprises three different temperature analysis approaches, in which firstly section 2.1 mentions the analytical approach of temperature prediction. Then, different numerical modeling techniques of temperature analysis have been presented in Section 2.2, and section 2.3 describes the experimental measurement methods for temperature in EDM. The last section (section 3) concludes the review study. Fig. 1 summarized the categories of this paper briefly.

2. Temperature analysis approaches

2.1. Analytical methods and theoretical considerations

The literature survey reveals that a great deal of theoretical research has been conducted by various researchers since 1971 to model EDM process thermally based on the mathematical equations of heat conduction into solids. Mentioned in section 2.1.2, the developed
models are investigated through applying either electro-thermal or electro-mechanical concepts. One of the very first electro-thermal models used by Snoeys and Van Dijck [15]. Van Dijck and Dutre [16] have implemented an electro-thermal model to calculate the volume of molten material. An exact series solution has been developed by Beck [17] to acquire transient temperature. Jilani and Pandey [18,19] and Lhiaoub et al. [20] have also analyzed EDM process by electro-thermal model. Determination of plasma channel size and resolidified layer thickness is obtainable by introducing electro-thermal models [21]. These models have been also investigated by Dibitonto et al. [22] and Patel et al. [23]. Besides electro-thermal models, Singh and Ghosh [24] have used an electro-mechanical model to estimate the material removal. This estimation is based on electrostatic forces acting on the surface of material, which is significantly dominant in removing the metal especially for short pulses.

Being numerous, all different parameters of EDM process are classified in three different groups namely process parameters, machining parameters and physical-metallurgical parameters of material. Each of these parameters can readily affect the performance of EDM as well as the surface integrity, accuracy and temperature distribution. Regarding to the numerous involving parameters, controlling various aspects of process is supposed to be really difficult. A majority of researchers have tended to investigate different aspects of EDM process by incorporating a set of main machining parameters such as pulse current, peak current, gap voltage, gap distance, duty cycle, pulse on-time, pulse off-time, polarity, and dielectric flushing pressure. Among the various machining parameters, pulse current, gap voltage and pulse on-time show the most remarkable impact on temperature distribution. Salonitis et al. [25] showed that the thermal characteristics such as specific heat, density, melting point, thermal conductivity and yield strength of the workpiece and electrode tools, gap between the workpiece and electrode tools, conductivity of the dielectric, flushing pressure, current of discharge and discharge duration, affect the fraction of heat energy generated in plasma channel and conducting the electrode as well as the actual energy for effective material removal. Numerous researchers have unanimously reported that the uncertainty nature of multiple discharges intensify the obstacles in analyzing EDM process theoretically. In fact, the electrical discharge in EDM process is of stochastic nature and high complexity to which scientific insight into both the macroscopic and microscopic fields is insufficient. So, in the past 60 years, a huge number of investigations have been accomplished to whether develop or improve different models. It is essential to be aware of various assumptions which many researchers have used in the mathematical models based on the existing hypothesis of their studies to simplify the analysis procedure. The most important assumptions are as follow:

- The cylindrical domain is usually considered as axisymmetric.
- EDM spark channel is considered as a uniform cylindrical column shape. The spark channel radius is often considered based on Ikai and Hashiguchi's formulation [26].
- The electrodes radius approximately 20 times greater than the radius of plasma channel and the outer side cylinder is adiabatic. Many researchers consider this assumption based on Van Dijck work.
- The widely-accepted distribution shape for heat flux due to the discharge is assumed to be Gaussian distributed.
- The EDM sparks are created in a vaporized medium in which a constant current can pass through it.
- A partial conversion of the electrical in thermal energy in the discharge channel due to the Joule heating effect can be neglected.
- The work piece and tool are homogeneous and isotropic.
- The thermo-physical properties of the workpieces, electrode tools and dielectric are temperature-independent. Averaged values of material properties are usually used.
- Heat loss due to convection and radiation is usually neglected and the heat transferred to the electrodes occurs mainly by conduction.
- The analytical studies are adapted for a single discharge.

### 2.1.1. Modeling of the heat source of EDM process

In the EDM process, an electrical energy is transmitted to the electrodes and an extremely high temperature is responsible for material melting. This high temperature is created due to the high intensity of current flowing through the gap between the electrodes. Many researchers have investigated energy distribution. Van Dijck showed that the amount of heat conducted into electrodes is more than 90% [27]. Xia et al. used copper for both anode and cathode and established a relationship between discharge duration and material removal rate. According to their results, for discharge duration greater than 20\(\mu\)s, the amount of material removal of cathode is higher than anode and vice versa [28]. This is because of variation of energy distribution into cathode and anode [29]. Koenig et al. have estimated the energy distribution of dielectric fluid and electrodes by measuring the temperature [30]. Xia et al. [31,32] have also reported that the percentages of energy distribution to cathode and anode are 25 and 40 respectively and the proportion of energy distribution for anode is always higher than cathode whether the EDM process is single discharge or multi-discharge. Kunieda et al. [33] have reported an approximate model in detail for distribution of total discharge energy as well as energy contribution distributed in the workpiece (see Fig. 2). According to the contribution of distribution energy into the workpiece in this model, the EDM thermal models can be derived by assuming the heat conduction problem as a preliminary mode of heat transfer between the molecules of both workpiece and electrode tools and the ions of plasma channel without any heat generation [34].

However, a widely-known theory is not still available because the nature of material removal mechanism accompanying the numerous sparks in the dielectric liquid is extremely complicated. Nearly all existing models usually apply the Fourier heat conduction equation as the governing equation with four boundary conditions and one initial condition [35]. The mathematical formulation for heat conduction problem is expressed as:

\[
\frac{1}{a} \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial r^2}
\]

where \(a\) is thermal diffusivity formulation \((m^2/s)\) which can be written as [13]:

![Fig. 1. A summary of three different methods of analyzing temperature distribution with widely-accepted techniques for EDM process.](image-url)
Some researchers usually take the melting heat phenomenon into account in the thermal diffusivity of the material \( \alpha' \) then the thermal diffusivity is given as [35]:

\[
\alpha' = \frac{K_t}{\rho C_p + \frac{K_t}{\rho}}
\]  

(3)

The initial and boundary conditions are assigned to solve the partial differential equation of the EDM process. Based on assumptions and the types of heat source, many attempts have been made to specify the boundary condition for EDM process. Earlier models have followed Zingerman’s shape of the heat source [36–39] and DiBitonto’s model [22]. Then other authors like Jilani [18,19], Beck [17,40], Dijck [16] and Snoeys [15] have considered a uniform distributed source for the heat flux. Predicting more precisely, Gaussian heat is the most reliable assumption which can describe the crater geometry. Based on Gaussian heat flux, Fig. 3 shows that four boundary conditions for heat conduction problem are introduced as follow:

\[
\frac{\partial T}{\partial n}(0, z, t) = 0
\]

(4)

\[
k(T) \frac{\partial T}{\partial r}(r, z, t) + h(T(r, z, t) - T_m) = 0
\]

(5)

\[
T(r, 0, t) = T_m
\]

(6)

And the initial condition is introduced as follow:

\[
T(r, z, 0) = T_m
\]

(8)

By solving either analytically or numerically the heat conduction equation, temperature curves can be elicited to predict the various characteristics of EDM process. For instance, temperature curves can be used to predict the crater depth or diameter accurately for meticulous calculation of material removal. The principal factors, affecting the precise estimation of material removal in a single spark EDM process, have been presented by Joshi et al. as the amount of heat input, the thermo-physical properties of the workpiece and the plasma channel radius [34]. During the solving of the heat conduction equation theoretically, different kinds of geometrical shapes of the discharge channel can have an unavoidable impact on the solution results of temperature distribution. In other words, one of the most particular characteristics that distinguishes different theoretical models is to how assume the heat source shape. The analytical prediction of heat input depends on the idealized geometrical shapes of the discharge channel (heat source). Earlier models have applied Zingerman’s shape of the heat source [36–39]. The most widely-used heat source shapes are most notably circular heat source, plane heat source and point heat source in which a finite radius is considered.

2.1.1. Plane heat source. Assuming an infinitely large radius for the heat source, the heat conduction problem is simplified to a unidimensional problem. Zingerman has reported the solution of heat conduction problem in which a plane shape for the heat source is considered as [39]:

\[
T(t) = \frac{(cT)^2}{8(\pi K)^2} \int_0^\infty \frac{dt}{(t - r)^2} \exp\left[-\frac{r^2}{4a^2(t - r)}\right]dr
\]

(9)

2.1.1.2. Circular heat source. Assuming a finite value for the radius of the heat source, it can be considered as circular shape. For this case, Zingerman [39] and Zolotykh [41] have applied the circular shape for heat source and found a quite well agreement between the analytical and experimental data. Zingerman [39] has reported the solution of heat conduction equation in which a circular shape for the heat source is considered as:

![Diagram of thermal model in EDM process with Gaussian heat flux and boundary conditions for heat conduction equation.](image)
2.1.1.3. Point heat source. Assuming a very small value for heat source radius and plasma channel for small discharge durations, the heat source is considered as an instantaneous point. Zingerman [39] has reported the solution of heat conduction equation in which a point heat source is considered as:

\[ T(t, r) = \frac{c_{p}^2}{8(\pi K)^2} \int_0^t \int_0^r Q(t - \tau) \gamma^2 \exp \left( -\frac{r^2 + x^2}{4a(t - \tau)} \right) dx \, d\tau \]

(11)

Hocheng has also proposed the solution for induced temperature for the instantaneous point heat source as [42]:

\[ T - T_0 = \frac{P}{8(\pi \alpha t)^2} e^{-\frac{r^2}{4\alpha t}} \]

(12)

In above relations, \( c \), the coefficient of volume specific heat varies by increasing temperature from normal temperature to the temperature of diffusion.

Different researchers have chosen different heat source shape. Earlier studies (for instance DiBitonto’s model [22]) have considered a point heat source, while other authors like Jilani [18,19], Beck [17,40], Dijkstra [16], Snoeyts [15], have considered a uniform distributed source for the heat flux. Not only is still the shape of heat source supposed as one of the most challenging situations in temperature prediction of EDM processes, but also the exact amount of heat flux energy generated in the plasma channel plays a key role in determining the temperature distribution in EDM process. In other words, the heat input definition in EDM process is established by the shape of heat flux as well as the exact amount of heat transferred to the workpiece. The exact solution of these mathematical equations depends on the amount of heat energy evolved per unit time [38,39].

2.1.1.4. The amount of heat input. With regard to the shape of heat source, \( q \), which is generated in the gap distance and then conducted to the workpiece and electrode tools can be defined for the disk heat source and point heat source [35]:

\[ q = \begin{cases} \frac{E_{\text{IV}}}{\pi} \text{diskheatsource} \\ \frac{E_{\text{IV}}}{2a} \text{pointheatsource} \end{cases} \]

(13)

where \( E_{\text{IV}} \) is the fraction of total energy conducted to the workpiece, \( r_{c} \) is the radius of the heat source at the workpiece surface, and \( r \) is the radial distance from the center of cylindrical coordinate origin. Although the proposed model is simple the accuracy of predicted temperature distribution for heat input has been proposed by Izquierdo et al. [44] for thermal modeling the EDM process:

\[ q(r) = \frac{Q_e U_{\text{ON}}}{2aR_{\text{plasma}}(t)} \exp \left\{ -4.5 \left( \frac{r}{R_{\text{plasma}}} \right)^3 \right\} \]

(14)

where \( Q_e \) is fraction of energy transferred to the workpiece. The exponent value (−4.5) used in these equations is in excellent agreement with measurements obtained using spectroscopy [44]. This value represents the shape of Gaussian heat flux and a higher or lower coefficient for the term \( \left( \frac{r}{R_{\text{plasma}}} \right)^3 \) illustrates how steep or wide the Gaussian heat flux is respectively.

Joshi et al. and Khan [34,43] have also used another Gaussian-based distribution for the heat flux as given:

\[ q(r) = q_0 \exp \left\{ -4.5 \left( \frac{r}{R_{\text{pc}}} \right)^3 \right\} \]

(15)

where \( q_0 \) is calculated as:

\[ q_0 = \frac{4.57F_{\text{IV}}VI}{aR_{\text{pc}}^2} \]

(16)

Having these equations are beneficial to estimate the important characteristics of EDM process such as surface roughness and MRR with regard to find out the relationship between the magnitude of the area of the heat flux and geometry of crater (diameter or depth of crater). In fact, having the knowledge of the heat source area can be further used to verify the theoretical and analytical derivations. But the exact measurement of the plasma channel radius and the area of heat flux are practically impossible. This is because of very high pulse frequencies and very short pulse duration of a few microseconds that makes the direct measurement extremely difficult. However, a number of attempts have been done so far to propose experimental approaches to estimate the plasma channel radius.

2.1.1.5. Plasma channel radius. There are two different types of equations to calculate the radius of the plasma channel:

I. Some researchers have expressed the plasma channel radius with respect to the time. It means that the plasma channel radius relation is time-dependent as below:

\[ R_{\text{plasma}}(t) = R_p t^n \]

(17)

Here, \( R_p \) defines the size of the plasma channel. It is an empirical constant and exponent \( n \) depends on the experimental condition. Different authors have considered different value for \( n \). Izquierdo [44] has proposed the value of \( n = 2 \), and Shuvra et al. [47], Philip et al. [23] has used the value of \( n = 3 \).

II. Another time dependent equation for plasma channel radius, \( R_{\text{sp}}(t) \), is proposed by Khan [43] as:

\[ R_{\text{sp}}(t) = K I^p t^m \text{ (\mu m)} \]

(18)

Two experimental studies have been separately conducted to determine the constants of above-mentioned equation. Salonitis et al. [25] have applied the following plasma channel radius \( r_p \) for a uniform heat source intensity distribution:

\[ r_p = 2040 \times (I_0^{0.41})^{(t_{\text{on}})^{0.44}} \]

(19)

Also, Joshi et al. [34] have used the equivalent approach for calculating the heat input radius:

\[ r_p = (2.04 - 3) \times (I_0^{0.41})^{(t_{\text{on}})^{0.44}} \text{ (\mu m)} \]

(20)

Substituting Eqs. (20) and (15) into Eq. (14) and rearranging them gives the following heat flux equation used in thermal model by Joshi et al. [34]:

\[ q(t) = 3.4878 \times 10^{14} \frac{F_{\text{IV}}}{t_{\text{on}}^{0.88}} \exp \left\{ -4.5 \left( \frac{t}{t_{\text{on}}} \right)^{0.88} \right\} \]

(21)
With regard to a comprehensive review on modeling of EDM Process [48], it is realized that it is necessary to determine the heat input and plasma channel radius as well as boundary condition to estimate the output characteristics of EDM process. Since the simulation of plasma channel is totally complicated, they must be determined by experiments [48].

During the temperature analysis of EDM process, the exact determination of heat flux is critical. Because not only does it affect the temperature distribution but also it contributes to the estimation of material removal rate and surface roughness. Salomits et al. [25] have numerically predicted the MRR by estimating depth of the depression crater as:

\[ s = \frac{Q \cdot \lambda}{\rho(L_\infty + C_p(T - T_0))} \]  

(22)

According to this theoretical equation, the depth of crater and consequently the volume removed per spark can be determined. However, using Eq. (22) material removal rate and surface roughness are determinable, it should be remarked that the geometrical shape of the crater created by spark is a contributing factor to determine either the depth or diameter of crater. DeBitonto [22] and Djick [16] model have used hemispherical crater cavity, Salomits [25] has assumed circular paraboloid geometry, Snoeys [15] and Beck [17,40] have predicted a bowl shape crater, and Jilani [18,19] has adapted a crescent like shaped cavity. Although, these assumptions are not in line with the real crater shape created in the real condition, Joshi et al. [34] have successfully predicted the real shape of cavity by incorporating the Gaussian heat flux distribution with shallow bowl shaped crater.

Prediction of depth of the crater is significantly pertinent to several parameters including the energy evolved in the discharge channel, the dimensions of the discharge channel and the thermo-physical properties of the workpiece. This point was also concluded by Eq. (22), represents that the amount of heat input, \( q_* \), (Eqs. (15), (14) (16) and (21)) contributes to determination of the depth of a crater by spark either for positive or negative polarity, long or short gaps, small or large thermal conductivity of material, and short or long pulses duration.

One more important factor should be noticed in all aforementioned equations is the exact fraction of total discharge power (\( F_c \)) which affects the heat flux distribution going to the workpiece. There are many different experimental studies have been conducted in this area of research. Rappaz [49] has stated that establishing the accurate energy distribution after a spark in EDM can reduce the average surface roughness of the workpiece to a desired value below 100 nm. It is explained by Yeo et al. [50] that considering the disk heat source, if the fraction of total discharge power is determined appropriately by either empirical or theoretical methods, the thermo-physical modeling of EDM process can be significantly improved. There are several studies proposed various values for energy fraction. Rappaz [49] has estimated 14.9% for total energy distributed into the workpiece for a particular condition of EDM process (discharge current 4 A and on-time pulse 25 μs). Izquierdo et al. [44] have applied an inverse simulation technique of thermal models and found that the 18.8% of total energy conducted into the workpiece for given EDM parameters. DeBitonto et al. [22] and Patel et al. [23] have estimated the fraction of the total discharge energy based on the theory of electron emission. They have also stated that the fractions of energy transferred into the anode and cathode, are 18% and 8.0% ± 1.0% respectively which can be varied with the pulse duration. Liao [51,52] has differently defined a new expression of SDE (specific discharge energy) to estimate the fraction of energy. SDE is a quantity that represents the needed real energy for removing a unit volume of material from the workpiece. DiBitonto [22] has estimated a power fraction of 18% for cathode, while the Snoeys [15], Djick [16], Beck [17,40], Jilani [18,19] have estimated 50%. With regard to the different estimations for \( F_c \) assumed by different authors, it is emphasized that the reasons for existence of errors among the various thermal modeling are unavoidable. Meanwhile, because these models have assumed a constant value of fraction of energy for whole limits of EDM parameters, these assumptions are not in good concurrence with the real condition of the energy distributed into the workpiece. Joshi et al. [34] have proposed an improved thermo-physical model in which the value of fraction of discharge energy is not fixed and changes with current and pulse duration. This model can predict the heat flux distribution more accurately and uses a higher fraction of energy for higher energy zones. Joshi’s model presents that considering the fractions of energy 0.183 and 0.183–0.2 for lower (up to 100 mJ) and medium energy zone (100–650 mJ) respectively leads to higher accuracy of thermo-physical models.

2.1.2. Analytical heat conduction equations

Because of taking different empirical assumptions into account by authors, there are various analytical models where the resulting characteristics differ. These models are analytically solved to predict temperature distribution to further use in estimation of the main characteristics like material removal.

The mechanism of the material removal is defined by the electro-thermal phenomenon where the material erosion takes place due to reaching the high temperature. High temperature and hydrostatic pressure of the plasma channel contribute to melt the workpiece material. At the end of on-time pulse, right after collapsing the plasma channel and releasing its pressure, a particular volume of the molten material is partially removed by splattering due to the bulk boiling phenomenon created in the dielectric liquid.

For long discharge durations (> 100μs) in EDM, melting is the principal factor for material removal. On the contrary, (< 5μs), melting does not account for short discharge durations because material does not get enough time to become adequately heated and consequently happens no melting. It has been reported that the electrostatic force acting on the workpiece can lead to the material removal and crater for short discharge durations [24]. Therefore, the boundary of created crater is taken as the isotherm curve of the melting temperature of the workpiece material [35].

A variety of approaches in analytical modeling have been used by many researchers to predict the temperature of workpiece and tools in EDM and then estimate the material removal. Some of the approaches apply DiBitonto’s model in which the heat source power is used, and some others are based on temperature source as used by van Djick. Each model is discussed in detail below.

2.1.2.1. Barrufet’s model

Barrufet has assumed a fixed circular disk source to solve the heat conduction equation governed on two dimensional EDM model. The analytical solution for temperature distribution in the workpiece is expressed as [53]:

\[ T(r, z, t, \alpha) = \frac{P_0}{2\pi a K_t} \int_0^\infty J_0(\lambda r) J_t(\lambda a) X \frac{d\lambda}{\lambda} \]  

(23)

where \( \lambda \) is a dummy integration variable and \( P_0 \) is the effective power of the energy source. \( a \) and \( P_0 \) are expressed as:

\[ X = e^{\alpha z} \left[ \text{erfc} \left( \frac{\lambda a + z}{\sqrt{\alpha t}} \right) \right] - e^{-\alpha z} \left[ \text{erfc} \left( \frac{\lambda a - z}{\sqrt{2\alpha t}} \right) \right] \]  

(24)

\[ P_0 = \pi \alpha K_t a^2 \]  

(25)

where \( J_0 \) and \( J_t \) are Bessel functions of the first kind of zero and first order respectively, \( a \) is the radius of the heat source and \( \text{erfc}(x) \) is the complementary error function. The above equation is the exact solution for the temperature distribution of the heat conduction equation with a fixed circular disk heat source.

2.1.2.2. Snoeys’s model

Snoeys has simulated the heat input into the workpiece by assuming a disk heat source which exists during the on-time pulse of EDM process. The outer surface of the cylinder is assumed insulated (Fig. 4). Considering the fraction of the energy...
transferred to the workpiece is 50%, the temperature distribution at the workpiece is expressed as:

\[
T(r, z, t) = T_0 + \frac{q_0}{K} \sum_{n=1}^{\infty} c_n \left( -J_0(\lambda_n r) + \sum_{m=1}^{\infty} \alpha_m \frac{\lambda_n}{\lambda_m} \sin(\lambda_m z) \right) \exp \left[ -\alpha \left( \lambda_n^2 + \mu_m^2 \right) t \right]
\]

(26)

c_n is a coefficient expressed as:

\[
c_n = \frac{2q_0 J_0(\lambda_n r_0)}{K \lambda_n (\lambda_n r_0)^2}
\]

(27)

where the roots of \( \lambda_n \) are calculated by \( J_0(\lambda_n r_0) = 0 \) (for \( n = 1, 2, 3, \ldots \)). \( J_0 \) and \( J_1 \) are Bessel functions of the first kind of zero and first order respectively.

2.1.2.3. Van Dijck's model. Van Dijck and Dutre have solved the partial differential equation for two-dimensional heat flow model for finite dimension in the z direction as well as infinite dimension which is similar with Snoeys's model. Finite case is a simplified version of the infinite dimension. The whole surfaces of electrodes and workpiece are considered to be insulated outside the heat source. The both electrodes and dielectric are initially considered at ambient temperature \( T_0 \). The fraction of the energy distributed into the workpiece is considered as 50%. The diagram of Van Dijck's model is schematically shown in Fig. 5.

The heat conduction equation has been solved using the superposition principle and separation of variables and the temperature distribution is expressed as [16]:

\[
T(r, z, t) = T_0 + \frac{q_0}{K} \sum_{n=1}^{\infty} c_n \frac{2}{\lambda_n r_0} \sum_{m=1}^{\infty} \alpha_m \frac{\lambda_n}{\lambda_m} \sin(\lambda_m z) \exp \left[ -\alpha \left( \lambda_n^2 + \mu_m^2 \right) t \right] \nonumber
\]

(28)

where the coefficients \( \alpha_n, \mu_m \) and \( c_m \) are expressed as follow:

\[
\alpha_n = \frac{2J_1(\lambda_n r_0)}{\cosh(\lambda_n l/2)(\lambda_n r_0)^2}
\]

(29)

\[
\mu_m = \frac{\pi}{2l} (2m-1)
\]

(30)

\[
c_m = \left( -1 \right)^m \frac{\lambda_n}{l} \left( \lambda_n^2 + \mu_m^2 \right) \frac{\cosh(\lambda_n l)}{l}
\]

(31)

where \( \lambda_n \) is the roots of \( J_0(\lambda_n r_0)=0 \) and \( l \) is the height of the finite cylinder (m) [16].

2.1.2.4. Beck's model. As it is illustrated in Fig. 6, the top surface of the workpiece is thermally loaded as a disk-shaped region. Apart from the heat flux region, the whole surfaces of the workpiece are assumed to be insulated [17,40]. This model has neglected the effects of melting heat.

Because this model is not specifically developed for EDM processes, the fraction of energy transferred to the cathode is not considered in the heat flux formulation. The temperature distribution is expressed as [17,40]:

\[
T(r, z, t) = T_0 + \frac{2q_0}{K} \left\{ \frac{r B(z, t)}{r_0^2} + \frac{1}{2} \sum_{m=1}^{\infty} C_m(z, t) \frac{J_0(\lambda_m r_0)}{(\lambda_m r_0)^2} \right\} \nonumber
\]

(32)

where the functions \( B(z, t) \) and \( C_m(z, t) \) are expressed as follow:

\[
B(z, t) = \sqrt{\alpha t} \text{erfc}\left( \frac{z}{2 \sqrt{\alpha t}} \right)
\]

(33)

\[
C_m(z, t) = -e^{-\lambda_m^2 t} \frac{1}{\sqrt{\pi \alpha t}} \left[ \text{erfc}\left( \frac{z}{\sqrt{\alpha t}} \right) + \text{erf}\left( \frac{\lambda_m}{\sqrt{\alpha t}} - \frac{z}{\sqrt{\alpha t}} \right) \right]
\]

(34)

where \( \lambda_m, T_0 \) and \( r_0 \) are defined similarly with Van Dijck's model.

2.1.2.5. Jilani's model. Convection and radiation are neglected in this model and the heat generated in the gap is assumed to be transferred into the workpiece by conduction. This study models both cathode and anode with semi-infinite dimensions. The fraction of total energy is assumed 50% and the top surface of the workpiece is assumed to be thermally struck by a disk heat source as illustrated in Fig. 7[21].

In this model, \( r_i \) the heat flux radius is assumed to not change during the on-time pulse in plasma channel. Except for the heat flux region, the whole surfaces of the workpiece and electrode tools are
totally assumed to be insulated. The heat flux at the top region of the workpiece is assumed to be circularly struck by numerous instantaneous point heat sources as illustrated in Fig. 7. The temperature distribution in the workpiece with the semi-infinite dimension in radial direction (r) is expressed as [19]:

\[ T(r, z, t) = \frac{q(r_c)^2}{K_e} \sqrt{\frac{2}{\pi}} \int_0^r \exp\left( -\frac{r^2}{4a^2t + r_c^2} - \frac{z^2}{4a^2t} \right) \frac{1}{(4a^2t + r_c^2)^{3/2}} dt \]  

(35)

During the on-time pulse, the temperature is assumed to remain constant at the center spot of the workpiece and equal to the boiling temperature of the workpiece material. The boiling temperature of workpiece material is derived as follow [19]:

\[ T_b = \frac{q_r}{K_e} \sqrt{\frac{\pi}{2}} \]  

(36)

2.1.2.6. DiBitonto’s model. DiBitonto has assumed that the radius of plasma channel at the center of workpiece surface is significantly smaller than the radius of plasma channel at the cathode surface. Hence, a one dimensional heat source is assumed as an instantaneous point instead of a disk shape for heat input, which leads to the spherical geometry. The fraction of energy conducted to the workpiece for erosion is approximated 18%. The melt front radius (r_{melt}) of the material is illustrated in Fig. 8.

The temperature distribution is expressed as follow:

\[ T(r, t) = T_b + \frac{q_r}{K_e} \sqrt{\pi} \left( \frac{r}{2\sqrt{at}} \right) \]  

(37)

DiBitonto has solved the governing equation using the following simplifying assumptions:

1. For the determination of melt fronts, the heat of fusion of the anodic material is negligible.
2. In the analysis, the average thermo-physical properties of the anodic material are used over the whole temperature range from solid to liquid melt.
3. The radius of heat flux at the anode surface is expanded at a specific rate of growth [22].

2.1.2.7. Model comparison. Van Dijck, Snoeys, Beck, and Jilani have used a disk heat source to solve the heat conduction equation and the models by DiBitonto and Barrufet have applied a point heat source and circular heat source respectively. Unlike the other models where the thermo-physical properties of the material are considered to be constant, DiBitonto’s model used an average thermo-physical properties value over the whole temperature range from solid to liquid melt. Except for Beck’s and DiBitonto’s models, models by Snoeys, Van Dijck, Jilani and Barrufet have considered the melting heat effects on the thermal diffusivity formulation. Also, aside from DiBitonto’s model, a two dimensional heat source model has taken into consideration in analytical solution of all models. All given models, with the exception of DiBitonto’s model where the fraction of total energy is 0.18, have assumed F_{c}=0.5. Table 1 summaries six given analytical models.

Bearing in mind that theoretical models can predict the temperature distribution, some models have the capability to predict the surface integrity and metallurgical features such as resolidified layer, white layer, etc. In fact, this point of view is accounted for the limitation of theoretical models except that proposed by Pandey and Jilani. They have suggested the theoretical model (Eq. (35)) which determines the thickness of the resolidified layer in the workpiece. This equation has been employed to calculate the exact locations of boundaries of boiling, melting and transformation isotherms [21]. These isotherms have been shown in Fig. 9.

Analyzing EDM process in terms of dielectric fluid flow field and debris distribution is another interesting area of research. Both Eulerian-Eulerian and Eulerian-Lagrangian approaches are usually used for Solid-Liquid two-phase flow simulation [54,55]. Employed by Li et al., Eulerian-Lagrangian approach is normally chosen for simulating the dielectric fluid flow field and debris distribution in the gap between electrodes in EDM process [56]. Considering velocity of dielectric and plasma pressure within the EDM process gap, the equations of continuity and momentum can be formulated for liquid instead of plasma. Eubank et al. have proposed a theoretical model consisting fluid dynamic, energy balance, and radiation equations. In terms of fluid mechanics, the continuity equation is written as [57]:

\[ \frac{\partial \rho_v}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho_v \upsilon) = 0 \]  

(38)

where

\[ \upsilon = \left( \frac{R_e}{r} \right) \frac{dP}{dr} \]  

(39)

and the momentum equation is as:

\[ \frac{\partial \rho_v}{\partial t} + \rho_v \frac{\partial \upsilon}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho_v \upsilon) = 0 \]  

(40)

Combining the momentum equation with radial velocity, the working fluid mechanical equation is expressed as:
<table>
<thead>
<tr>
<th>Model</th>
<th>Assumption(s)</th>
<th>Geometry/Dimension</th>
<th>Heat flux shape</th>
<th>Heat flux fraction</th>
<th>Energy fraction</th>
<th>Heat flux radius</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrufet (1959)</td>
<td>Temperature-independent thermo-physical properties</td>
<td>Cylindrical/Two-dimensional</td>
<td>Fixed circular disk heat source</td>
<td>Constant</td>
<td>0.5</td>
<td>Increasing with time</td>
<td>Radiation and convection are neglected, other effects are considered, obtained crater profile is hemispherical</td>
</tr>
<tr>
<td>Snoeys (1971)</td>
<td>Adiabatic condition for upper area of electrode</td>
<td>Cylindrical/Two-dimensional</td>
<td>Circular heat source</td>
<td>Constant</td>
<td>0.5</td>
<td>Not applicable</td>
<td>No guideline for the outer cylinder radius</td>
</tr>
<tr>
<td>Van Dijck (1974)</td>
<td>Semi-infinite cylinder</td>
<td>Cylindrical/Two-dimensional</td>
<td>Circular heat source</td>
<td>Constant</td>
<td>0.5</td>
<td>Approximation of heat flux radius is not available</td>
<td>Obtained crater profile is hemispherical</td>
</tr>
<tr>
<td>Beck (1981)</td>
<td>Non-variable heat flux</td>
<td>Cylinder</td>
<td>Disk heat source</td>
<td>Increasing with time</td>
<td>0.5</td>
<td>Not applicable</td>
<td>No guideline for the outer cylinder radius</td>
</tr>
<tr>
<td>Jilani (1986)</td>
<td>Temperature-independent thermo-physical properties</td>
<td>Cylindrical/Two-dimensional</td>
<td>Disk heat source</td>
<td>Not applicable</td>
<td>0.18</td>
<td>Not applicable</td>
<td>No relationship for calculating HAZ is available</td>
</tr>
<tr>
<td>DiBitonto (1989)</td>
<td>Adiabatic condition for upper area of electrode</td>
<td>Cylindrical/Two-dimensional</td>
<td>Disk heat source</td>
<td>Not applicable</td>
<td>0.18</td>
<td>Not applicable</td>
<td>No relationship for calculating HAZ is available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation and convection are neglected, other effects are considered, obtained crater profile is hemispherical</td>
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</tr>
</tbody>
</table>
Because of this, the thermal conductivity, the speciﬁc heat and the heat transfer coefficient are assumed to be constant, the exact analytical solution is existent using the classical method called separation of variables [59]. But if a temperature-dependent thermal conductivity can result in a non-linear problem, solving the heat conduction equation leads to more realistic results for temperature distribution, it is recommended to take other sources of nonlinearities (Eqs. 43 and 44) into consideration for the future studies.

Despite the analytical solution method, the numerical approach can be used as an alternative method to predict the temperature distribution. Next section will review the various numerical methods applied by different researchers.

2.1.3. Solution methods of nonlinear heat conduction equations in EDM

In this section of the review, the current research trends carried out by researchers on the different solution methods of non-linear heat conduction equations are reviewed. Basically, the heat equations are divided into linear and non-linear. One of the sources of nonlinearity in heat conduction equations is mainly due to variable thermo-physical properties of materials like temperature dependent thermal conductivity. In most cases, it is too hard to tackle with the difﬁculties of solving non-linear equations. In fact, solving the non-linear equations in regular forms available solution methods is analytically impossible [58]. Therefore, endless efforts of researchers have been directing to ﬁnd innovative ways to solve them or even to minimize the error of solution results. In the case of linear heat conduction equation where thermal conductivity, speciﬁc heat and heat transfer coeﬃcient are assumed to be constant, the exact analytical solution is existent using the classical method called separation of variables [59]. But if a remarkable temperature variation exists within a thermal process like EDM, the thermo-physical properties of materials are not constant. Because of this, the thermal conductivity, the speciﬁc heat and the heat transfer coeﬃcient are generally formulated as functions of temperature as given:

\[
k(T)=k_0[1 + \beta(T-T_0)]
\]

\[
C(T)=C_0[1 + \beta(T-T_0)]
\]

\[
h(T)=h_0[1 + \beta(T-T_0)]
\]

By substituting the above expressions into the heat equation, the ﬁnal form of equation will be transformed to a non-linear form. Since the exact solution of the nonlinear problem is relatively diﬃcult, many researchers have focused on ﬁnding possible solutions. One of the widely-accepted methods available in the literature of semi-analytical methods is known for perturbation method (PM). Perturbation methods have used by many mathematical research to solve nonlinear problems. It is based on the existence of a small/large parameter, which is called perturbation quantity [60–62]. Despite the numerical methods, some other promising analytical methods have been recently proposed to approximately solve nonlinear equations, among which homotopy method [63], and homotopy analysis method (HAM) [64,65], homotopy perturbation method (HPM) [66] and variational iteration method (VIM) [67], differential transform method (DTM) [68], and Adomian Decomposition Method (ADM) [69]. Besides these methods, the variational homotopy perturbation method (VHIM) is considered as a capable and reliable method of solving a large class of either linear or nonlinear differential equations [70].

For the case of EDM heat conduction equation, where a temperature-dependent thermal conductivity can result in a non-linear problem, after substituting Eq. (42) into Eq. (1), expanding and rearranging, the ﬁnal form of governing equation for cylindrical coordinate system is expressed as:

\[
\frac{\kappa(T)}{\rho_0} \left( \frac{\partial^2 T(r, \theta, z)}{\partial r^2} + \frac{1}{r} \frac{\partial T(r, \theta, z)}{\partial r} + \frac{\partial^2 T(r, \theta, z)}{\partial \theta^2} \right) + \rho c \frac{\partial T(r, \theta, z)}{\partial t} = \frac{\partial^2 T(r, \theta, z)}{\partial z^2}
\]

Appraising the non-linear terms in above equation makes the solution very diﬃcult. All has been done so far, having the highest similarities to Eq. (45) is Aziiz’s formulation [71,72]. He has tried to solve a two-dimensional, steady state heat conduction equation in a square plate with variable thermal conductivity using perturbation method to construct the second-order expansion solution for a Cartesian coordinate system as given [71]:

\[
(1 + \lambda \theta(X, Y)) \left( \frac{\partial^2 \theta(X, Y)}{\partial X^2} + \frac{\partial^2 \theta(X, Y)}{\partial Y^2} \right) + \lambda \theta(X, Y) \left( \frac{\partial \theta(X, Y)}{\partial X} \right) + \lambda \theta(X, Y) \left( \frac{\partial \theta(X, Y)}{\partial Y} \right) = 0
\]

Due to the lack of adequate studies to analytically deal with the heat conduction equations where thermo-physical properties are temperature dependent, continuous advancements in solving the non-linear EDM equations still need to be accomplished. Because some materials have speciﬁc characteristics which aﬀect the temperature behavior, considering variable thermo-physical properties in calculating the heat conduction equation can eﬀectively lead to higher accuracy of temperature distribution results. So, since there are some sources of nonlinearity in Eq. (45), solving the heat conduction equation leads to more realistic results for temperature distribution, it is recommended to take other sources of nonlinearities (Eqs. 43 and 44) into consideration for the future studies.

Despite the analytical solution method, the numerical approach can be used as an alternative method to predict the temperature distribution. Next section will review the various numerical methods applied by different researchers.

2.2. Numerical methods

Numerical approach is one of the economical options used by many researchers to solve either linear or non-linear equations including heat conduction equation. With this approach it is possible to estimate various output characteristics of EDM process including the maximum temperature, temperature distribution, surface roughness and removed material from both anode and cathode in EDM process. Since the maximum temperature in the discharge channel characterizes the behavior of thermal models, some researchers have concentrated on evaluating this parameter. Imposing excessive thermal loads on the surface of materials, phase transformation, surface crack, white layer, HAZ, etc. may happen. With regard to this fact that the determination of the geometrical characterization of metallurgical consequences of EDM process is often critical, numerical methods can readily help researchers to develop predicting models to address this matter. For instance, models like the one developed by Das et al., in which the process parameters are used to predict transient temperature distribution can predict deformation, microstructure and residual stress as well [47].

Various numerical studies in the area of EDM temperature analysis, can be essentially classiﬁed into two broad categories: (1) Finite Diﬀerence Method and (2) Finite Element Method. The FDM is the oldest and the easiest-to-use one and basically uses a Taylor expansion method.
series to approximate the differential equation. Topologically, this technique uses a square network of lines to construct the discretization of the partial differential equations and is based on three possibilities for finite difference, namely forward difference, backward difference and centered difference. On the contrary, the FEM is the most flexible one in terms of dealing with complicated geometries and complex boundary conditions. Comprising either implicit-based method or explicit-based method, this technique uses one or both of them to solve partial differential equation. The later one suits well for dynamic and heat transfer problems.

2.2.1. Finite difference method

Shankar et al. [73] have used the finite element method to solve the field equations for electric potential and temperature in three different regions (i.e., spark, anode, and cathode). They have drawn the isotherms by solving the below equation for electric field and temperature equation by implicit finite difference method [73]:

\[ \begin{align*}
\text{Electric Field Equation} & : \int_E \sigma \left( \frac{\partial \phi}{\partial x} \right) \, dx \, dz \\
\text{Temperature Equation} & : \int_E \int_R \rho C_p \frac{\partial T}{\partial t} \, dx \, dz
\end{align*} \]

This study has compared the computed results obtained from the above-reported models with experimental data to estimate the MRR and REW (Relative Electrode Wear). The final results show that pulse current, pulse duration, and gap distance have the maximum impact on MRR.

Mahdavinejad et al. [74] have proposed a semi-empirical model, based on statistical and thermal-mechanical methods. They have used a finite difference method to develop a circular heat source model with time dependent radius on a semi-infinite cylinder in cylindrical coordinates with considering Joule heating generation in SiC workpiece. The finite difference forms of both electrical potential and temperature distribution equations are expressed as [74]:

\[ \frac{1}{(\Delta r)^2} \left[ \frac{1}{2} \left( T_{i+1}^n + T_{i-1}^n \right) + T_{i}^{n+1} - 2 T_{i}^{n+1/2} - T_{i}^{n+1/2} \right] = 0 \]

And

\[ T_{i}^{n+1} = \frac{\alpha A T}{(\Delta r)^2} \left[ \frac{1}{2} \left( T_{i+1}^{n+1/2} - T_{i-1}^{n+1/2} \right) + \frac{\alpha A T}{(\Delta r)^2} \left( T_{i+1}^{n+1/2} - T_{i}^{n+1} + T_{i-1}^{n+1} \right) + \frac{1 - 2 \alpha A T}{(\Delta r)^2} T_{i}^{n+1} \right] \]

\[ \left[ 1 - 2 \alpha A T \right] \left( \frac{\alpha A T}{(\Delta r)^2} \right) T_{i}^{n+1} = \frac{\alpha A T}{(\Delta r)^2} \left( T_{i+1}^{n+1/2} - T_{i-1}^{n+1/2} \right) + \frac{1}{(\Delta r)^2} \left( \frac{\alpha A T}{(\Delta r)^2} \right) T_{i}^{n+1/2} \]

In order to numerically solve the differential equations of electrical potential and heat conduction, the central difference method and explicit method have been used in the finite difference method. Maximum temperature has been calculated by this method in the depth and surface of SiC and Steel workpieces for different levels of current and pulse duration [74].

Ben Salah et al. [75] have used below finite difference scheme to present numerical temperature distribution results of EDM process to estimate the surface roughness and MRR:

\[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{2} \left( \beta_T T_{i+1,j} + \beta_T T_{i-1,j} + \beta_T T_{i,j+1} + \beta_T T_{i,j-1} \right) - 1 \]

Considering the temperature-dependent thermal conductivity, the thermal results are closely matching with experimental data [75].

Izquierdo et al. have used the finite difference method considering the temperature fields within the cathode generated by multiple sparks to be further used for predicting the surface roughness and material removal rate. Three-dimensional equation for temperature distribution is expressed by the finite difference schema as below:

\[ T_{i,j,k+1} = T_{i,j,k} + \frac{k T_{i,j,k} - T_{i,j,k-1}}{\rho C_p \Delta x \Delta y \Delta z} - k T_{i,j,k-1} - \frac{\Delta x \Delta y \Delta z}{\Delta x \Delta y + q (\Delta x \Delta z + \Delta z \Delta y + \Delta y \Delta z)} \]

Three important characteristics of the discharge including the shape and size of plasma channel, energy conducted into the cathode, and the mechanism of material removal has been estimated using the inverse identification from the numerical results [44].

The EDM heat conduction equation has been solved by Wu-Yao Chiou et al. [76] to obtain the thermal conductivity and discharge power using an inverse heat conduction algorithm. They have compared the temperature distribution of the analytical solution with the numerical solution [76]. The heat conduction equation is solved analytically by using the separation of variable method. The solution for the temperature distribution is expressed as:

\[ T(r, z, t) = \sqrt{2} t^{-1} \sum_{n=0}^{\infty} \frac{J_0(k_n r)}{r} \cdot \frac{\sin(2n+1) \pi z}{2n+1} \]

where \(J_0(k_n r)\) and \(J_1(k_n r)\) are Bessel functions. The heat conduction equation of EDM process has been discretized in two dimensions to obtain the temperature distribution by using the finite difference method as followed [76]:

\[ \frac{1}{(\Delta r)^2} \left( T_{i+1,j} - T_{i,j} \right) = \frac{1}{(\Delta z)^2} \left( T_{i,j+1} - T_{i,j} \right) - \frac{1}{(\Delta x)^2} \left( T_{i+1,j} - 2T_{i,j} + T_{i-1,j} \right) \]

\[ \left[ 1 - 2 \frac{(\Delta x)^2}{(\Delta r)^2} \right] \left( \frac{(\Delta z)^2}{(\Delta r)^2} \right) T_{i,j} = \frac{1}{(\Delta x)^2} \left( \frac{(\Delta z)^2}{(\Delta r)^2} \right) T_{i+1,j} - \frac{1}{(\Delta z)^2} T_{i,j+1} \]

\[ T_{i,j} = \frac{1}{(\Delta r)^2} \left( \frac{(\Delta z)^2}{(\Delta r)^2} \right) T_{i+1,j} - \frac{1}{(\Delta z)^2} T_{i,j+1} \]

2.2.2. Finite element method

A numerical simulation using code-based finite element model has been developed by Yadav et al. to estimate the temperature field. This study shows that how the temperature distribution can be further employed to estimate the thermal stresses generated by Gaussian distributed heat flux of a single discharge EDM process. This study has also investigated the influences of current discharge and duty cycle on both temperature and thermal stress distribution. The results have illustrated that the thermal stress exceeds the yield strength of the workpiece material [77].

Shuvra Das et al. have presented Finite Element Method for EDM process to obtain temperature distribution for a single spark [47]. The transient temperature profiles, residual stresses, liquid- and solid-state material transformation and final crater shape have been simulated by DEFORM software. The input parameters of this simulation are pulse duration, power input, etc. A particular feature of FEFOR3D is the ability to estimate the crater geometry as well as thickness of white layer and HAZ.

From the surface of the workpiece to the depth, the shapes of residual stress profiles are most frequently different from the experimental results. Ghani et al. have used FEM to evaluate both temperature and residual stress in X2CrNiMo17-12-02 steel. It has been revealed that the patterns of generated profiles are different at the
surface regions of workpiece whereas quite the same in deeper layers of heat affected zone [78]. This is because of the fact that FEM never takes into consideration the stress relaxation by surface cracking and superficial hardening due to surface carbon and hydrogen.

Revaz et al. [79] have solved the transient heat conduction equation using numerical methods on the basis of inverse calculations to obtain the temperature distribution in the workpiece for a single spark. The numerical analysis has been performed in axisymmetric Neumann-type boundary conditions with given thermal parameters. Beside the numerical approach, experimental temperature measurements have been performed to characterize fundamental properties of plasma channel such as power fraction and expansion of plasma channel. Finally, in this method, a comparison between numerical and experimental data has been made.

Marafona [80] has presented a 3D FEM model based on Joule heating effect in the dielectric liquid to predict the maximum temperature reached in the gap as well as the material removal from anode and cathode. The innovation of the numerical analysis performed by Marafona is because of considering Joule heating factor in the EDM process and the obtained results illustrate the better correlations with previous experimental and theoretical results. Marafona’s temperature distribution results with five different temperature levels have been shown in Fig. 10 for both electrode tools and workpiece for the current intensity of 2.34 A. This study has implemented this kind of temperature distribution image to estimate the melting volume per spark in both electrode tools and workpiece. The melting temperature curves can delimitate a specific area which is further used for measuring the geometry of crater on both electrodes. This area is calculated with the aid of image processing technique which is further accompanied with Pappus–Guldinus theorem to measure the volume of created crater. This theorem states that the volume of a solid of revolution generating by rotating a plane figure about an external axis is equal to the product of the area and the distance traveled by its geometric centroid. So, according to this study, it is possible to estimate the output MRR and surface roughness in the EDM process.

Pérez et al. have employed an innovative numerical methods and a local micron-scale temperature measuring technique to examine the heat effect on the mechanical and metallurgical properties of steel machined by EDM process. They have calculated the thermal field, residual stress, phase dynamics and the influence of multiple sparks on the cathode by inverse analysis, non-equilibrium numerical methods and stress analysis [81].

In a similar work, a MATLAB-based Finite Element model, simulating a single spark condition has been developed by Allen and Chen for the micro-EDM machining of molybdenum workpiece. In this paper, temperature profiles, material removal and residual stress have been analyzed using the thermo-physical model. The effects of pulse duration of EDM process on the crater geometry dimension and the tool wear percentage have been also investigated. The actual dimensions of craters have been experimentally measured using the optical evaluation and SEM techniques [82]. One of the outstanding aspects of this study is to consider all elements with a temperature above the melting point killed. Using this update model leads to higher prediction accuracy in temperature distribution.

A similar thermo-physical model has been proposed by Kansal et al. to predict MRR based on the analysis of the temperature distribution profiles and material transformations. Various effective aspects of the powder mixed EDM (PMEDM) like material ejection efficiency and enthalpy (phase change) have been taken into account to assess the thermal behavior of material and then predict the material removal mechanism. Under the same machining conditions, PMEDM can produce a shallower and smaller crater in comparison to normal EDM process [83]. The main weak point of this study is to consider the PMEDM process for a single spark condition. It is asserted that the results of this study can be further implemented to predict the distribution of temperature and residual stress, surface cracks and metal flow. The effects of latent heat and evaporation have been considered in a more realistic and reliable way:

\[ C_n = C_p \frac{L_m}{2\Delta T} \text{for} T_{n-1} - \Delta T \leq T \leq T_{n+1} + \Delta T \]  

(54)

and

\[ C_n = C_v + \frac{L_v}{2\Delta T} \text{for} T_{n-1} - \Delta T \leq T \leq T_{n+1} + \Delta T \]  

(55)

Joshi and Pande [84] have reported an intelligent model for EDM process using finite element method and artificial neural network (ANN). Considering more realistic assumptions for a single spark EDM process, including Gaussian distribution of heat flux, time-and energy-dependent spark radius, they have developed a two-dimensional axisymmetric thermal model to estimate three output parameters. This model is based on Neural Network method to establish a relationship between the input parameters (on-time pulse, discharge power, duty factor) and output parameters (material removal rate, shape of crater cavity, and tool wear rate) and then it has been validated by experimental and analytical results. One of the reasons that the results are more accurate in this study is to follow a comprehensive and integrated methodology (Fig. 11). This methodology has a remarkable merit that the results are based on the accurate FEM instead of experimental data gathering, which could be particular in terms of cost, time consumption and error.

Joshi and Pande have also used the same procedure to investigate the influence of current discharge, voltage discharge, duty cycle and discharge duration on the above-stated output parameters. Compared to their prior study, according to Fig. 12, the outstanding privilege of this study is providing the optimized conditions in both the roughing and finishing machining [85].

XIE Bao-cheng et al. have developed an axisymmetric three-dimensional thermo-physical model using finite element method to estimate the temperature distribution as well as MRR. Considering the realistic characteristics such as energy fraction, discharge duration-current based equation for spark radius, Gaussian distribution and
plasma channel radius, this study provides a theoretical foundation for mechanism of material removal by simulating a single spark of EDM process [86]. The model used in this study benefit from considering the latent heat and evaporation. On the contrary, neglecting the radiation in erosion mechanisms can be a disadvantage.

Some researchers tend to describe the EDM process thermo-electrically to model important EDM characteristics like MRR based on thermo-electrical mechanism. A thermo-electrical model has been used by Weingärtner et al. [87] to estimate the MRR for two separate materials, brass (CuZn39Pb3) and steel (AISI1010). This study is distinguished from the other FEM-based studies by considering the different types of heat source and investigating its effects on MRR. The results suggest that a time-dependent heat source is more reliable for predicting the shape of craters than disk and point heat source.

In an attempt to simulate the EDM process by FEM, Kalajahi et al. have predicted the temperature profiles along the depth and radius of the workpiece. They have used the obtained temperature distribution to calculate MRR theoretically. The influence of the EDM parameters on heat distribution of the cathode has been investigated to establish a quadratic polynomial regression model which relates the input parameters with MRR [88].

In order to simplify the FEM procedure, researchers have usually considered the energy distribution factor based on previous studies. Kalajahi et al. have compared the numerical results with experimental data to precisely predict the energy distribution by introducing a novel procedure [88]. Thus, because the features of the workpiece material and machining conditions differ widely from one to another, determination of this factor, individually, is suggested for each particular study.

It is asserted that the evaporating pressure and its effects on molten zone deformation have been rarely considered in previous studies. The evaporating pressure can be predictable if the evaporating temperature is predicted and the evaporating temperature can be predictable if the latent heat is considered. This pressure acts as plasma channel pressure and causes the molten metal to be pushed up. Plasma channel distribution is as like as Gaussian distribution. The induced deformation in molten pool can be calculated by studying the fluid flow equations. As the molten zone in the workpiece is incompressible, the equation of continuity and Navier-Stokes equations can be applied for a viscous incompressible axisymmetric flow.

Wang et al. [89] have studied the molten metal deformation in a single spark EDM process in gas medium using finite element method. This study has analyzed the morphology of crater with edge raised, by using the simulation of process based on the thermal analysis. Calculated temperature distribution has been applied as thermal load on the workpiece and the plasma pressure has been simultaneously applied to simulate the crater edge. The deformation of molten metal has been calculated by developing the equations of continuity and Navier-Stokes in fluid analysis (These equations can be easily accessible in [90]). According to the results of this study, because the diameter and depth of crater created in the gas are respectively larger and smaller than kerosene as dielectric, dry finishing is suggested to acquire better surface roughness.

Mohanty et al. [91] have analyzed the effects of EDM parameters on MRR, wear rate and residual stress using the coupled thermal-structural model in finite element method. They have used a 2-Dimention axisymmetric model for the thermal analysis to compute the temperature distribution. The experimental results of MRR, wear rate and residual stress have been also provided to develop equations using regression analysis.

Non-dominated sorting Genetic algorithm (NSGA II) is a powerful optimization tools and adapted well to multi-objective optimization problems. The obtained solutions in pareto fronts, which are optimal solutions can be used in empirical models. The advantages of such empirical models is that they can be further used to improve the efficiency of the EDM process and also other output parameters like what evaluated in Mohanty’s study (surface roughness as an output parameter [91]) by selecting the ideal process parameters.

Guo et al. have developed a multi-scale finite element analysis of EDM process to understand the fundamental mechanisms of erosion in a single spark EDM process. Investigation of the effects of current and duration of pulse on the temperature profiles and the crater formation presents that the superheating and melting are two fundamental mechanisms of erosion in the EDM process. As an important result of this study, melting front is affected by discharge duration. The melting front recedes and advances at long discharge duration and high discharge current respectively [92]. A fascinating novelty in this study
is to construct a function for discharge current to avoid the issue of numerical singularity at nanoscale time. They have developed the function based on the variation curve of current gap in the EDM process.

Zhang et al. [93] have proposed a new different method for investigating the characteristic of plasma in the EDM process. Different shapes of heat flux such as Gaussian heat source, circular heat source and point heat source have been considered within a finite element analysis to find the effects on the crater geometry. The boundary of the melted volume in the crater has been determined by the isothermal surface obtained from thermal-physical model as well as metallurgical analysis. In other words, the boundary of resolidified material in the crater has been determined by metallurgical method and then the boundary of molten zone has been calculated by the thermo-physical model. The numerical data of this study reveals that the Gaussian heat source with a power fraction of nearly 50% is remarkably consistent with the actual geometry of crater. Based on this study, by considering the actual material removal efficiency, the results of material removal are found to be closer to real values of material removal from the molten area. The distinguished point of this study is taking the volume of recast material into consideration. The total molten area is calculated by isothermal curves of thermo-physical model.

Zhang et al. has also used the metallurgical method to determine the diameter of plasma and energy distribution [94]. To do that, they have compared the boundary of molten material in the crater obtained by FEM with the experimental data resulted by metallurgical method. The obtained results show that the expansion of the plasma diameter and power density are two significant factors affecting the material removal and energy efficiency. For instance, for short pulse durations, the energy efficiency and material removal are much greater than when long pulse duration is considered for the EDM process.

Kuriachen et al. have simulated a single-spark micro EDM to estimate the temperature distribution and crater geometry on the Titanium-6Al-4V workpiece. This study has developed a three-dimensional model to indicate the temperature distribution at different capacitance and voltage levels along the radial and depth directions. The shape and size of the craters have been experimentally recorded by using a scanning electron microscope (SEM) and a Taylor Hobson 3D profilemeter to validate the results of thermal simulation [95]. The main difference of this study is to use finite volume method (FVM) to analyze a transient heat conduction model. This method discretizes the heat conduction equation explicitly based on integral form or flux form.

In general, the temperature distribution results of the numerical studies have been obtained to be further used in characterizing different aspects of the EDM process like MRR, the volume of crater, surface roughness, etc. Some other research has used thermal analysis to investigate the different metallurgical layer dimensions. For example, Shao et al. have used realistic EDM conditions to simulate the crater formation using EDM. In this study, the recast layer has been estimated by investigating the isothermal curves [96].

By interpreting the different numerical-based studies, a very common result can be inferred. Taking three different factors namely the temperature-dependent properties for materials, the latent heat of fusion and vaporization into account can make the simulation results more close to the realistic results [97].

Although the numerical simulation techniques are applicable for researchers to estimate the important characteristics more conveniently, the absolute certainties of obtained results are not guaranteed. Hence, the experimental methods are implemented by researchers to make their findings confirmed.

2.3. Experimental measurement methods

The temperature as a basic thermal parameter of the EDM processes is usually preferred by researchers to be estimated using analytical and numerical simulation method and due to the measurement challenges, it is rarely measured experimentally. It is worth mentioning again that the lack of experimental temperature observations is certainly correlated to the complex nature of the EDM process. The complexity is due to the very short discharge durations, excessive temperatures, presence of a dielectric fluid and the micro-scale electrode gap [98].

In order to measure temperatures of the workpiece, tool electrode, dielectric fluid and plasma in the EDM process, a variety of techniques have been employed by researchers. In this section, we review the widely-used techniques as well as the experimental setups and their requirements. The outstanding temperature results and needed equipment are also described.

A review on papers published in the last 60 years shows that the researchers’ studies on temperature measurement in EDM process can be categorized into two major classes. Some of the studies have investigated measuring the temperature of workpiece, tool electrode, and dielectric fluid and some have particularly focused on measuring the temperature of plasma. Almost, the vast majority of researchers tend to use the thermocouples to measure the temperature of former while others working on measuring the temperature of the latter apply the imaging and optical emission spectroscopy method [33]. Basically, thermocouples have not only widespread usage but also many advantages. They are: (1) simple and flexible in construction, (2) easy in remote measuring, (3) simple in operation condition and signal processing, (4) versatile and useful for vast temperature ranges, (5) low cost, and (6) relatively fast responding, depending on size. However, the advantages are tempered by the possible associated sources of uncertainty and the relative complexity of the thermocouple system [98,99]. When applying the thermocouple, it is necessary to take into account some considerations on unavoidable errors caused by lag and settling, radiation, immersion, material non-homogeneity of thermocouple wires, etc. which are fully described in [98].

2.4. Temperature measurement of electrodes and dielectric

Takao Utsumi [100] in 1971 has based the Maxwellian portion of velocity distribution of the vapor atoms to measure the temperatures in vacuum media. His innovative method was introduced for the first time as an applicable technique for process in which various simultaneous phenomena such as electron emission and ionization of metal vapor atoms occur. Applying a quadrupole mass analyzer accompanied with the time-of-flight technique, he successfully measured the cathode spot temperature for 30 different metals.

Van Dijk has used a different method to analyze the temperature distribution in the workpiece. He asserted that the metallurgical examination of the surface of the workpiece submitted to numerous sparks can give a clear understanding of the gradients and magnitude of the temperatures [27].

Revaz et al. have conducted various experimental studies so far to characterize various aspects of EDM process. For the first time, they presented two special types of temperature measurements which have been performed in both scales of the single and global discharge. For global discharges, they measured in-depth temperature of cathode affected by repetitive discharges. For the case of single discharge, they designed a special device to measure the temperature response with high resolution. Basically, because of the difficulties of measuring the temperature including the excessive temperatures, very localized thermal load and short duration of discharge, they manufactured a thermal device containing 12 Au-Pd thin film thermocouples. Using this device, providing a local resolution of 20 μm, the maximum temperature measured at 2–100 μm from the center of the discharge (4 A, 25 μs, 20 V) was recorded 600 °C [101].

Revaz et al., in a separate study [102], have used the same device, containing 14 thin film Au–Pd thermocouple junctions, to observe the
surface transient temperature variation $\Delta T(r, t)$. As illustrated in Fig. 13, the device was allowed to be mounted as near as possible to the spark zone, on the backside of a thin steel foil workpiece (50 $\mu$m thickness) submitted to the discharge on the topside. The maximum temperature measured during a single spark was 280 °C. The main advantage of using this technique is the ability to measure excessive temperature gradients.

It is worth mentioning again that during the EDM process, the local temperature at the surface of the workpiece reaches at the temperature vaporization of the material ($T > 2000^\circ$C)\(^{[101]}\). Each spark removes metal from both cathode and anode by melting and vaporization. Thus, the occurrence of phase transformation from solid to liquid and also liquid to vapor during the EDM sparks is highly likely \(^{[47]}\). It is claimed that removal mechanism in EDM is because of melt-splashing for high energies ($E > 0.03$J) \(^{[103]}\) and vaporization for low energy ($E < 0.001$J) \(^{[103]}\). Lhiaubet and Meyer have claimed that the proportion of vaporized material to the total removed material is around 1.25 – 4.10% at anode \(^{[104]}\) and 1.15 – 1.90% at cathode \(^{[104]}\).

Revaz et al. \(^{[79]}\) have also measured the temperature and geometry of melted region to scrutinize the properties of the plasma channel. They patterned 14 Au-Pd thermocouples at 14 different locations on the surface of a thin steel foil to acquire sequential measurements. They combined the temperature data with observations of the recast layer geometry to determine the exact power fraction as well as the plasma channel radius as a function of time ($r_{\text{plasma}}(t) \propto t^n$). The results showed that the power fraction and exponent $n$ in the equation of plasma channel radius are 10% and 0.2 respectively.

In addition to the implementation of the aforementioned special micro-thermocouple, Revaz et al. have introduced another supportive setup for temperature measurement in EDM. They measured the thermal response to a single spark by means of a special high speed framing IR CCD camera (infrared charge-coupled device) based on thermography measurements. As a result of this study, excellent agreement was found between the two temperature measuring methods and the maximum measured temperature recorded by both equipment was 590 °C \(^{[105]}\).

The advantages of measuring temperature by IR CCD cameras are notably their low expense, effectiveness for high temperatures and high local resolution (4.5 $\mu$m). On the contrary, they have weak spectral responsivity specially at shorter wavelengths (0.27 $\mu$m – 1.05 $\mu$m) and their restricted ability to measure the short range of 500 – 1000 °C \(^{[98]}\).

Harminder Singh \(^{[106]}\) has used J-type Iron/Constantan thermocouples to measure the temperature of tool electrode, workpiece and dielectric fluid (as shown in Fig. 14). The thermocouples with a range of $-40$ – 750 °C, were located at different positions to survey the exact distribution of input discharge energy. The temperature ranges with a resolution of 0.1 °C were room temperature to approximate 100 °C for different discharge currents (2 – 24 A) and pulse durations (20 – 200 $\mu$s).

In the study of Peter Fonda et al. \(^{[107]}\), the temperature of workpiece has been measured to investigate the effects of duty factors on MRR during the EDMing the Ti–6Al–4V workpiece. To accomplish this, internal temperature of the workpiece was recorded by means of a K-type thermocouple inserted into the workpiece. The tip of the thermocouple was located to the nearest possible position to the spark zone. The maximum recorded temperature of the workpiece was around 40 °C at a duty factor of 50%. According to the results of this study, the distance between the spark zone and thermocouple tip should be set so as to avoid the destructive effects of high voltage on the thermocouple performance. In this study, as illustrated in Fig. 15, this

Fig. 13. SEM view of the crater due to a single spark (100$\mu$m, 22V, 5A) and the position of junctions of thermocouple. The crater diameter in the melted zone is approximately 70$\mu$m whereas one of the heat affected zone is around 216$\mu$m \(^{[102]}\).

Fig. 14. Schematic view of thermocouple locations. The walls of tank were covered by glass wool and Teflon insulation is prepared for lateral surfaces of workpiece and tool electrode \(^{[106]}\).
distance was selected 7 mm away from the spark region.

2.5. Temperature measurement of plasma

Generally, Optical emission spectroscopy (OES) is a classical plasma diagnostic which can perform several important plasma measurements such as chemical composition, densities, electric and magnetic fields present in the plasma and temperatures. The OES can measure the plasma temperature based on spectroscopic analysis. That is, the OES consists in the spectral analysis of the light emitted in the visible region by the plasma. The light is dispersed in a spectrograph, generally by a grating, and detected by photodiodes, a photomultiplier or a CCD camera.

This technique has revealed that the temperature of plasma in EDM reaches a peak of 6000–7000 K [108–111]. Albinski et al. [112] in 1996, have determined the temperature of plasma in EDM process. They implemented the spectroscopic analysis to evaluate the temperature of plasma by assessing the intensity of the Fe-I line spectrum emission. They could capture the amount of intensity of the radiation emitted from the discharge region by using photomultipliers and monochromators for the wavelengths of 411.854 and 413.29 nm. The corresponding intensity of the emitted radiation was further used to estimate the temperature of plasma. The relative time dependent temperatures were in the range of 8000 –10000 K. This range was acquired under the individual experimental EDM conditions (anode: M1E, cathode: NC6 and dielectric: cosmetic paraffin).

Natsu et al. [111] have also elaborated on measuring the temperature distribution of arc plasma by using spectroscopic analysis. The true values of temperature results were calculated by Abels’ inversion method. They used this technique to investigate the effects of various machining conditions including gap distance, discharge current and electrode shape on the temperature distribution. The results showed that a larger gap distance, thinner electrode and higher discharge current led to greater plasma temperature. The results also illustrated that the plasma temperature, depending on the EDM conditions, can vary from 4000 to 8000 K.

Descoeudres at al. [45] have used both imaging and optical emission spectroscopy techniques to introduce a spatio-temporal characterization of the plasma in EDM process. Applying tow techniques resulted in profiles of the electron density and of the electron temperature which are useful for EDM plasma modeling. Images captured right after a discharge revealed that the particles removed from the workpiece were incandescent and their temperature was approximately 2200 K.

Fig. 16 shows the variation of temperature for two different gap distances of EDM process in which the discharge current and discharge duration are 40 A and 300 μs respectively [33].

Klocke et al. [113] have measured the plasma temperature by assessing the emitted radiation of spark region. They applied a high resolution ultrafast camera containing a beam splitter, a macro lens and three charge coupled device (CCD) cameras to measure the emitted radiation. Each of the CCD cameras were connected to distinct filters, ranging from 450 to 700 nm. Characterizing the cameras against a tungsten lamp at high temperature of 3000 K, they calibrated the system and then recorded the emission intensities during the time intervals of 3μs. The obtained data were then applied in solving a modified Max Planck equation for the process temperatures, ranging widely from 4469 to 6153°C.

Ramkumar et al. [114] have used optical spectroscopy (as shown in Fig. 17) to measure the temperature and electron density in the micro-EDM process. The average temperature of plasma was about 6170 K. The results obtained from the optical spectroscopy method showed that the discharge gap and electrode size play an important role in determination of the plasma characteristics. Greater discharge gaps and smaller size of electrode resulted in higher plasma temperature and electron density.

3. Conclusion and possible further research

This paper tried to cover all possible available published papers to categorize the various approaches of predicting temperature in EDM process. The vast array of research works carried out within the last 60 years, ranging from the analytical approaches of temperature distribution analysis to the numerical and experimental techniques was discussed and a summary of the different studies about the temperature prediction methods was provided for each approach. The review of the research trends on the temperature analysis showed that researchers’ studies can be divided into three separate approaches, namely the analytical, numerical and experimental analysis. For each introduced approach, the main objectives were the same: to enhance the accuracy of temperature prediction, to facilitate choosing the approach (or a combination of approaches) for temperature distribution analysis, to promote the prediction procedures of output parameters based on temperature distribution and finally to assign the prerequisites of modeling and facilities needed for experimental studies. In order to make more progress in the total accuracy of temperature prediction, some desirable enhancements are still needed for future scope of work, hence some important limitations of current models and useful recommendations are provided in the following section.

3.1. Future works

- First of all, a comprehensive theoretical model containing the
variable thermo-physical properties is recommended for more accurate prediction of temperature curves. It is important to consider the real behavior of materials in analytical and numerical analysis. For some materials like Titanium alloy (Ti-6Al-4V), thermo-physical properties such as thermal conductivity and specific heat capacity are dependent to temperature variation. In order to obtain more accurate prediction of the temperature curves, it is strongly recommended to take the temperature-dependent properties into account instead of constant thermo-physical properties. Although many researchers like Snoeys, Van Dijck, Bech, etc. have attempted to model the EDM heat conduction equation to estimate the temperature, many simplifying assumptions have been considered so as the modeling leads to non-realistic results. Comparing the analytical methods with numerical studies shows that the analytical methods prevents taking the temperature dependent thermo-physical properties into consideration. This is because of difficulties existing within the solving of the non-linear heat conduction equations. Assuming the constant properties in calculations can lead to simplicity but inaccuracy of the temperature estimation.

Another worth-mentioning limitation is taking into consideration the classical Fourier heat conduction theory. Since the pulse duration is extremely short, this theory may not be able to calculate the transient temperature distribution accurately. So, investigation on a comprehensive theoretical model containing the non-Fourier law of heat conduction is another open ended field in which research work can be carried out.

The numerical methods, in this study categorized as FEM and FDM, are suggested as powerful tools to be used for estimating the temperature distribution with considering the variable thermo-physical properties.

The integrated powerful approaches including FEM-ANN-GA, like what Joshi and Pande proposed, are recommended for choosing the optimum parameters. The modeling and optimization approaches are always found quite effective and robust in predicting the output results of machining processes as accurate as possible. Furthermore, these combined methods can provide the flexibility for researchers to select the optimum parameters meeting their needs.

The fraction of total energy plays important role in accurate estimation of heat distribution and accordingly in accurate prediction of temperature. Further studies in this direction are still needed to establish an empirical-theoretical relation for determining the exact amount of input discharge energy for different electrode materials and different machining parameters. It is very difficult to predict a theoretical relation for fraction of energy for thermo-physical models due to the apparent incongruities and grain size data. The early researchers conjectured the same value of fraction of heat energy transferred to electrodes for all machining parameters in their models.

Since there is not yet a generally-accepted theory for plasma channel radius, it is also recommended to investigate the influence of various parameters on the plasma channel radius to construct a relation for further use in both theoretical and numerical thermal models.

Time-dependent heat flux, time-dependent current and time-dependent voltage are introduced to the pre-existing thermal models as the most effective process parameters to modify the temperature distribution. Applying the constant heat flux, current and voltage either in theoretical or numerical models can deteriorate the total inaccuracy in predicting the temperature distribution.

- A partial conversion of the electrical in thermal energy in the discharge channel may happen due to a phenomenon called Joule heating effect. In other words, the electrical energy dissipated by current flowing across the interface is normally released as heat on the surfaces electrodes. Mathematically, this heat is calculated as a fraction of electrical energy (thermal energy due to electrical current) and added to the heat flux and radiation as boundary conditions in the heat conduction equation. Neglecting or considering Joule heating effect can increase the discharge channel temperature and consequently influence the MRR in EDM process. Taking both electrical and thermal equations into consideration is recommended to enhance the total accuracy of temperature distribution, especially while working with semi-conductor substances like SiC.

- Almost all existing thermal models neglect the possible effects of material microstructure on temperature distribution during the EDM process. Meanwhile, since the microstructural changes may happen due to imposing excessive thermal loads on the workpiece, a need for deeper investigations on how microstructural changes and grain size can affect the thermo-physical properties (especially thermal conductivity and specific heat) and temperature distribution is felt.

- With regard to the cost and practical difficulties of experimental techniques for determining the thickness of different metallurgical layers in HAZ, it is recommended to study of workpiece surface quality through the theoretical methods like Pandey-Jilani model. Determining the thickness of white layer, molten-resolidified layer and recrystallization layer of the workpiece by emphasizing the theoretical-based models is strongly suggested.

- In terms of practical temperature measuring methods, it is recommended that more investigations in this area of research are needed to identify a well-adapted measuring method. In particular, a deep focus on the non-contact measuring methods is essential. Most of the recent published papers about temperature measurement techniques have unanimously concentrated on measuring the temperature by means of thermocouple and optical emission spectroscopy for the electrodes and plasma respectively. In the EDM processes, the temperature is not still measured easily due to the very small gap and short duration of discharges. The importance of measuring temperature in research becomes vital when we see the existing measuring techniques have still many weak points.

Finally, it is asserted that the above-mentioned research areas are expected to become an industrial tool in the author’s hand to provide categorized information for further research to analyze the temperature distribution and to facilitate characterizing the EDM process.

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Fig. 17. The electrode geometry and optical set-up. This technique is applied to better focus the plasma emission light onto a very small slit (0.1 x 0.5 mm) of the spectro-scope with two 1/2 lenses and high resolution camera (752 x 580pixels) [114].


