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A SIMULATIVE STUDY ON THERMAL EFFECT OF STATIC ELECTRICAL ARC ON SURFACE HEAT DISSIPATION FOR DIFFERENT ELECTRODE CONFIGURATIONS USING ANN

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Abstract: In this study, thermal characteristics of the electrical arc for different electrode configurations were investigated and their results were presented. In order to observe the thermal effects of the arc, time dependent heat transfer which occur on electrode surface because of arc, and temperature distributions were simulated by a software using Finite Element Method, on the electrode systems that are composed of three different electrode types (plane-plane, rod-plane, and sphere-sphere electrodes). In addition to that, temperature distribution in plane-plane electrodes was calculated analytically and compared with the numerical simulation results. Besides, the simulations were performed for 1 mm, 2 mm, and 3 mm electrode gaps respectively, to see the effect of distance between electrodes on temperature distribution. It was analyzed by numerical simulations, how the temperature of the arc column and arc period is changing the temperature distribution. During the numerical calculations, temperature distributions over the electrode surfaces have been carried out by training an artificial neural network (ANN) and compared with both simulation and numerical results. All of the results are given graphically. Consecutively, from studies on heat dissipation of the arc it is found that area of electrode surface is dominant on this effect.

1 INTRODUCTION

Electrical arc occurs in circuit breakers, arc heaters or arc welding apparatus is a hot, luminous and noisy electrical discharge that causes large scale of temperature due to joule heating. One of the physical properties is heat dissipation of the arc [1]. When an electrical arc occurs between two electrodes, temperature distribution along the electrodes depends on some parameters such that arc duration, gap spacing, plasma temperature and electrode shape as well [2-5].

Temperature of the arc can be hazardous on electrodes ignites between them when cannot be extinguished properly. It causes evaporation of electrodes and burns the insulation [6]. So it is important to know the temperature distribution characteristic of the metallic electrodes when they are exposed to arc fault. Numerical calculations for heat dissipation are commonly used with basic heat transfer formulas. However, sometimes it is very difficult to solve these kinds of problems due to the complexity of the geometry. The thermal systems don’t always have symmetrical and simple geometric shapes. It can contain asymmetrical parts and unconventional forms as well. Finite element method is very useful to solve these kinds of complex geometries rather than numerical calculations [7].

Intelligent systems and soft computational methods such as artificial neural network (ANN) and fuzzy logic have been successful in estimating temperature and heat transfer along the electrode surface. Compared with the classical methods, soft computational methods are fast converging algorithms. These methods needs some time to but have enough accuracy.

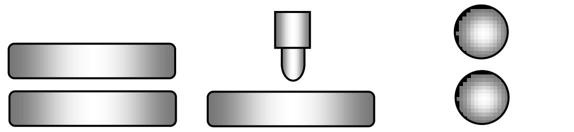
In this study, parameters of arc that influence the temperature and heat dissipation are investigated using ANN. A finite element method based analysis program provides input data for training the network. Three different electrode shapes that are plane, sphere and rod are used for modeling setup. To see the effect of arc parameters on temperature and heat distribution, each of the parameters are applied and changed their values for three electrode configuration respectively and then systems are simulated for specific boundary conditions and values.

2 THERMAL ANALYSIS USING FINITE ELEMENT METHOD

In order to observe the thermal effects of the arc, time dependent heat transfer which occurs on electrode surface because of arc, and temperature distributions are simulated by a software using finite element method, on the systems that are composed of three different electrode types (plane-plane, rod-plane, and sphere-sphere electrodes).

Simulations are performed for 1 mm, 2 mm, and 3 mm electrode gaps respectively, to see the effect of electrode gap on temperature distribution. It is analyzed by the simulations, how the temperature of the arc column and arc duration is changing the temperature dissipation.

The geometry of the system is based on real electrodes used for high-voltage tests. Plane electrodes have 10 mm thickness, 75 mm diameter and 3 mm curvature radius. Diameter of sphere electrodes is 10 cm. The last one is rod electrode with 10 mm diameter and 50 mm length. Rod also has 120^{o} of apical angle. All the electrodes are made of brass. Considering electrode geometries are shown in figure 1.



(a) (b) (c)

Figure 1: Used electrode types: a) plane-plane; b) rod-plane; c) sphere-sphere electrodes

In literature, arc between the metallic electrodes is considered as a cylinder with a radius r, arbitrarily assumed to be 0.1 cm. Arc column length is bounded with the distance between the electrodes h and generally h is chosen as h >> r.

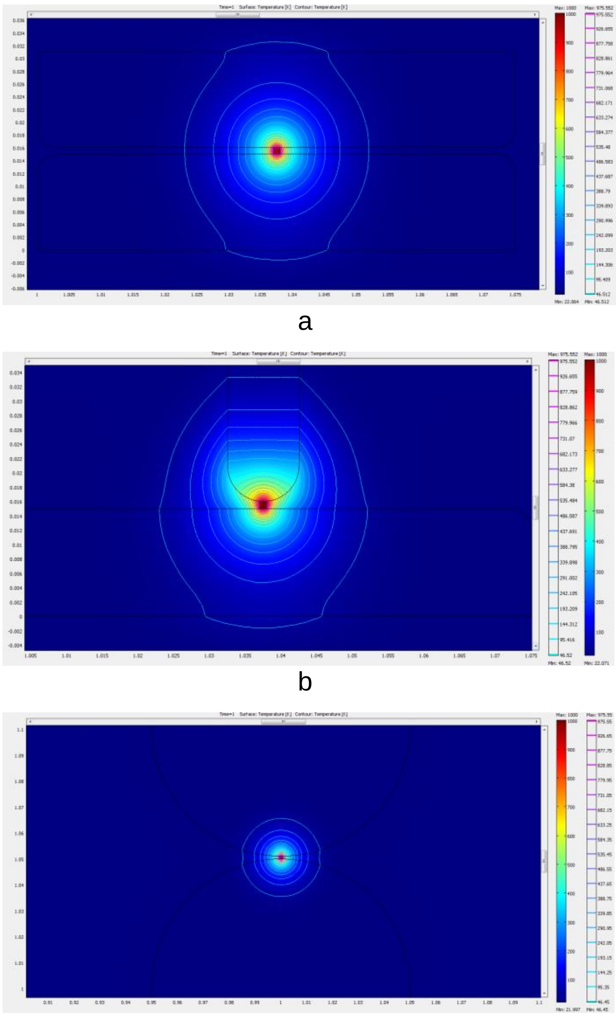
Thermal properties chosen for the subdomain of the geometries are given in table 1. Thermal analysis needs three material parameter such that thermal conductivity, density and heat capacity. Arc plasma conduct huge amount of heat easily in other words, its thermal conductivity must be high enough. Thermal properties of silver are equal enough to the arc plasma, for this reason thermal characteristics of silver are selected for modeling thermal arc.

Table 1: Thermal properties of system parts

Subdomain	Unit	**Air**	**Arc plasma**	**Brass electrodes**
Thermal conductivity (k)	W/(m·K)	0.0257	429	116
Density (rho)	kg/m^3	1.205	10500	7140
Heat capacity at constant pressure (C)	J/(kg·K)	1006	235	390

Initial temperatures at the simulations are assumed as 22 ^{0}C for air and 24 ^{0}C for the electrode surface temperature. These values are remained constant until the end of the simulations. Arc column temperature was changed for the simulations which deal with the arc plasma temperature effect on heat dissipation and fixed to observe the electrode shape and arc duration effects.

Heat transfer depends on time, so simulations were done as time dependent analysis. Current zero crossing assumed at time zero and after the arc ignites temperature values calculated for three different time interval 0-1 s, 0-2 s, 0-3 s with 0.01 s step size. Tolerance of the computations is chosen as 0.0010. Figure 2 shows the simulation results for the three electrode systems. These results were also used as input data for the neural network training mentioned in the following part.



a

b

c

Figure 2: Temperature distributions of electrode systems: a) plane-plane; b) rod-plane; c) sphere-sphere electrodes

3 ARTIFICIAL NEURAL NETWORK

The role model for soft computing is the human mind and nature itself. Neural network is the well known soft computing method that has begun to use from mid 1950s. Rather than traditional numeric optimization methods, ANN can be easily applied very complex and nonlinear systems to solve both control and identification problems [8].

Heat transfer problems vary and usually contain nonlinearity. Sometimes it becomes very difficult to solve these types of problems with numerical approaches. ANN is an alternative and reliable way.

The FEM simulation results were also used as training and validation data for neural network. In order to train the ANN, several points from arc column to electrode edge with an equal range were taken along the surface of the plane electrode and the temperature data of the related points were calculated. For this purpose, rod plane electrode system having 1 mm gap spacing was simulated with 3000 ^{o}C arc temperature and 3 seconds arc duration. 70 data points along the electrode surface were taken into account.

For plane electrode dissipation, 50 data points that cover the whole workspace and reflect the all characteristic of the temperature distribution of the electrode surface were used from among the 70 data to train the NN. 20 data were also chosen for validation as well. On the other hand 48 data with 32 of them for training and 16 of them for validation were used for the rod electrode because of the smaller surface area than plane electrode. The total training and validation (bold data) data for plane electrode distribution is given in table 2.

Table 2: Training and validation data for plane electrode system

mm	^{o}C	mm	^{o}C	mm	^{o}C
0,5	3000,00	**12,5**	**654,78**	24,5	295,67
1	2225,99	13	631,47	**25**	**287,36**
1,5	1956,97	13,5	609,17	25,5	279,45
2	1775,64	**14**	**587,81**	26	271,94
2,5	**1637,41**	14,5	567,35	**26,5**	**264,81**
3	1525,34	15	547,74	27	258,06
3,5	1430,91	**15,5**	**528,94**	27,5	251,68
4	1349,22	16	510,89	28	245,66
4,5	**1277,21**	16,5	493,58	28,5	240,00
5	1212,79	**17**	**476,96**	**29**	**234,69**
5,5	1154,51	17,5	461,01	29,5	229,72
6	**1101,28**	**18**	**445,70**	30	225,09
6,5	1052,31	18,5	431,00	30,5	220,80
7	1006,97	19	416,90	31	216,84
7,5	**964,76**	**19,5**	**403,36**	31,5	213,21
8	925,30	20	390,38	**32**	**209,90**
8,5	**888,26**	20,5	377,93	32,5	206,92
9	853,38	**21**	**366,00**	33	204,27
9,5	**820,44**	21,5	354,56	33,5	201,94
10	789,25	22	343,61	**34**	**199,96**
10,5	759,65	22,5	333,13	34,5	198,34
11	731,52	23	323,11	35	195,92
11,5	**704,72**	**23,5**	**313,53**		
12	679,18	24	304,39		

The algorithm consists of feed-forward back-propagation parts. Firstly the learning rate η is chosen and predefined the maximally allowed or desired error E_{des}. After the weight matrices of the layers are initialized, on-line training is performed and the new training pair to the hidden layer neurons in order to calculate the outputs from the hidden and output layer consecutively. The last step of the feed-forward part is finding the E_p the value of sum of the square error cost for the given weight matrices and the data pair applied to the network. Back-propagation part is used for weight updates. This part starts with computing the error signal δ_{ok} of the output layer and the hidden layers error terms backward. At the end the weights are updated by using error rates. This loop is repeated for each epoch until reaching the desired error value E_{des} [9].

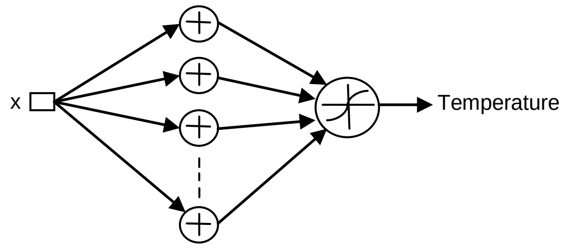
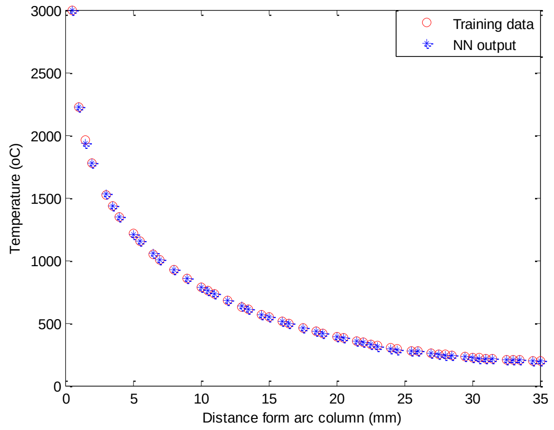


Figure 3: Neural network structure of the considered system

Figure 3 shows the multi-layer feed forward NN architecture used for temperature distribution. Structure of the algorithm is related to nonlinearity and complexity of the problem. The problem we deal is one dimensional coaxial cylindrical system, so only one hidden layer is enough. However, the number of hidden neurons should be chosen. For this reason tree growing method was used to configure the ANN structure. The network was initialized and the weights were calculated for several numbers of hidden neurons respectively. After that the NN results were compared with the validation data set for every network configuration. For plane electrode temperature distribution it was seen that the best configuration is one hidden layer with nine hidden neurons. Besides this, for the rod electrode distribution two hidden layers with two and six hidden neurons respectively were chosen as the best solution.

Gradient descent with adaptive learning rate (GDX) and Levenberg-Marquardt (lm) back-propagation algorithms were used as learning algorithm. It was shown that accuracy of Levenberg-Marquardt back-propagation cross validation results is higher than the GDX. Also LM converges with less epoch number that means faster than GDX.

Network configuration related to plane electrode training sequence consists one hidden layer with 9 hidden neurons. 0.0000001 was chosen as the error goal for the network. In Figure 4 neural network output of training data and neural network output of validation data are given. The results were gained just in 867 epochs.



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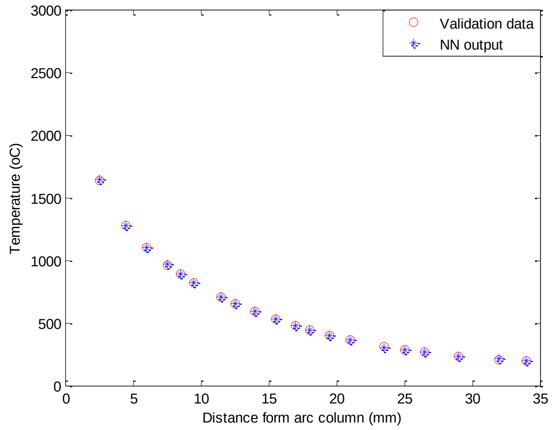

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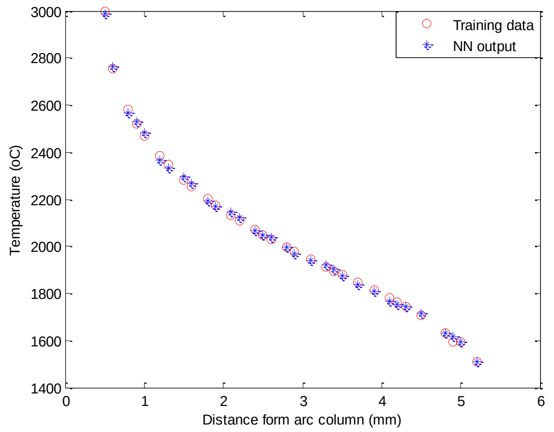
Figure 4: Neural network output for planar electrode system: a) training data; b) validation data

Figure 5 shows temperature dissipation along the surface of the rod electrode according to ANN results. There are some differences compared with the previous simulations. Rod electrode surface area is smaller than plane electrode so fewer data was collected. For this reason ANN structure was slightly changed. Two hidden layers with 1 and 4 neurons respectively were used for structure. Network converged after 1000 epoch unlike ANN for plane electrode.



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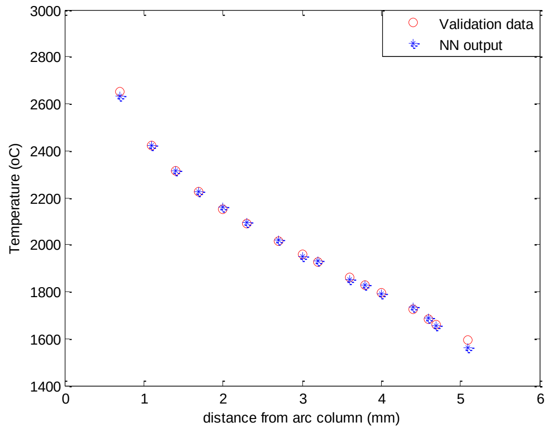

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Figure 5: Neural network output for rod electrode system: a) training data; b) validation data

4 RESULTS OF ANN SIMULATIONS

Temperature distribution is highly dependent on the electrode surface area. Different electrode systems such that plane, rod or sphere expose different dissipation characteristics. In Figure 6, temperature dissipation along the electrode surface of the three systems given 1000 ^{o}C arc plasma can be seen.

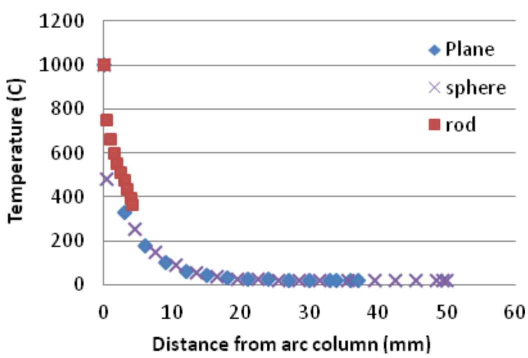
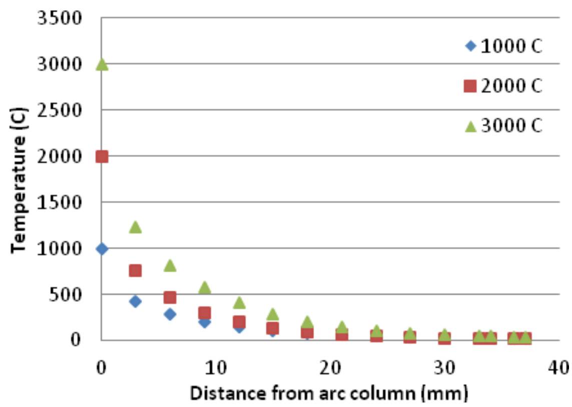


Figure 6: Surface temperature distribution for the different electrodes

As can be seen in the figure above, surface temperature distribution on sphere and plane electrode systems are almost the same. This is because the two systems' total surface areas are little less than equal to each other. On the other hand, rod electrode has relatively less surface area. Hence same amount of heat that diffuses smaller area yields higher temperature. Also plane and sphere electrodes have much more cool area rather than rod electrode.

Plasma column is the only heat source for arc discharges. Therefore, arc column temperature is proportional to surface heat transfer. In order to see the temperature influence of plasma column, simulations were done by using same gap distances and arc durations under fixed column temperature for three electrode systems. Figure 7 shows that temperature along the electrode surface very depend on temperature of the arc plasma. This effect can be seen easily for rod electrode due to its less surface area.



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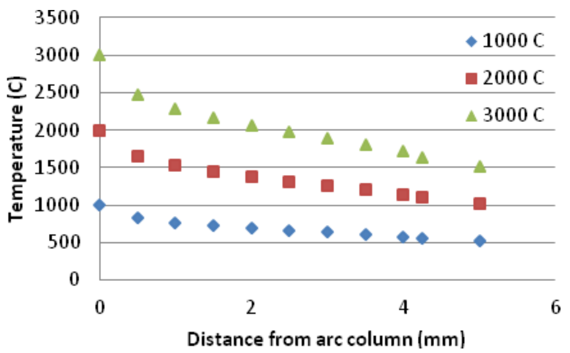

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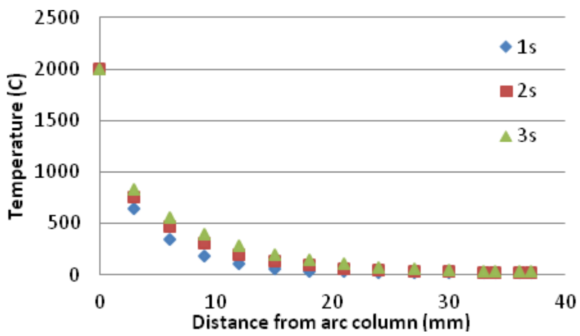
Figure 7: Electrode temperature dissipation with respect to distance from arc column: a) plane electrode; b) rod electrode

After the contact separation, arc ignition is extinguished after a couple of time. Meanwhile, temperature on the electrode surface is getting higher with the heat transfer during the arc duration [11, 12]. This state can be seen in figure 8. According to figures it can be said that arc duration on plane or sphere electrodes with large surface areas is less effective than rod electrode.



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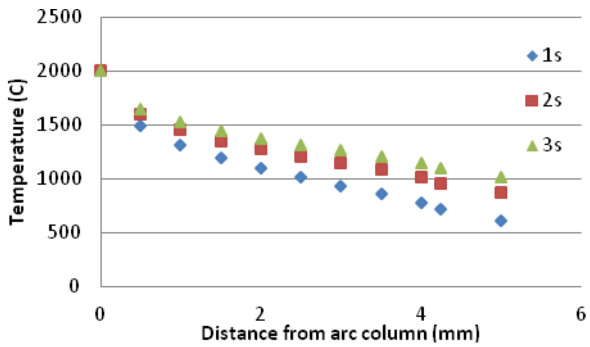

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Figure 8: Electrode temperature dissipation with respect to distance from arc column: a) plane electrode; b) rod electrode

5 CONCLUSION

In this paper, surface temperature characteristics caused by electrical arc have been analyzed by using FEM simulations and ANN. Arc has been modeled with a cylindirical column between the metallic electrodes for the simulations. Data obtained from the simulations have been used as input in order to train neural network for each electrode system. Simulations show that temperature dissipation is directly related with surface area, arc column temperature and also duration of arc. Besides, ANN is a reliable, fast, and accurate way to be able to estimate temperature values of unknown points from collected data.

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