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A NEW METHOD TO OPTIMIZE GEOMETRIC DESIGN OF ELECTROSTATIC SENSOR ELECTRODES USING PARTICLE SWARM OPTIMIZATION

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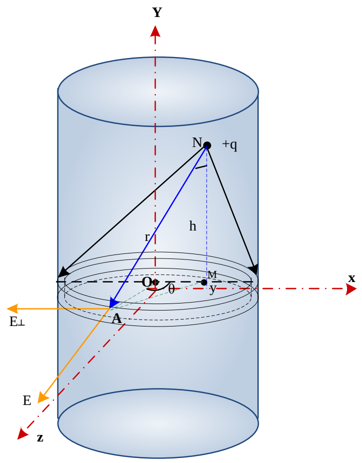
Graphical abstract



Abstract

Optimization of electrostatic sensor electrodes plays a significant role to achieve more homogenous spatial sensitivity. Particle swarm optimization (PSO) is a simple method that has attracted many attentions in recent years. In this paper, the physical sizes of several electrodes for electrostatic sensors are optimized using the PSO technique. Spatial sensitivity of electrode is considered as objective function in this method. Additionally, the thickness and length of electrode are described as physical characteristics of electrode, which need to be optimized. In order to verify this optimization method, different electrodes are applied in laboratory. The optimal value of thickness and length of electrode according to the optimization and experimentation are 5mm and 6mm, respectively. As a result, there is a great agreement between the optimization and experimental results.

Keywords: Electrostatic sensors, spatial sensitivity, velocity measurement, particle swarm optimization, electrode design

1.0 INTRODUCTION

Electrostatic sensors do not need an external signal source, which makes them robust and cost-effectiveness. Additionally, these sensors are appropriate to measure the velocity of particles in many laboratories and industries[1]. Velocity measurement is important to measure the mass flow rate[2] and the concentration of solid particles[3, 4]. Non- uniform spatial sensitivity is calculated by taking the difference between the correlation velocity and mean particle velocity. Consistency of spatial sensitivity is significant to decrease the flow regime[5]. Therefore, geometric sizes of electrostatic sensor electrodes should be optimized not only to reduce the discrepancy between the correlation and mean particle velocity but also to achieve more homogenous spatial sensitivity.

Optimization of electrostatic sensor electrodes is the major contribution in this study. Hence, a particle swarm optimization (PSO) technique due to its simplicity and reliability is applied to optimize the physical sizes of electrodes. A PSO algorithm was applied by Kennedy and Eberhart [6, 7] while it follows the bird flocking or fish schooling. A PSO could attract numerous attentions due to its advantages such as simplicity and reliability. Generally, a PSO has two versions- local version and global version [8, 9].

In recent years several methods such as GA, ANSYS, and FEM have been applied to optimize these electrodes. Genetic algorithm (GA) is an evolutionary computation method with evolution parameters including cross over and mutation. While PSO does not consists of evolution parameters. Qian *et al*. put forward the GA method to optimize the length and thickness of electrodes [10]. But the clear results had not indicated in that research. Moreover, ANSYS was another approach which is applied to optimize the electrostatic sensors in recent years. ANSYS has pioneered the improvement and application of simulation technique to solve the engineering issues. The results of ANSYS for optimization of these sensors are completely variable in each run. Therefore, this method is not dependable to use. Finite element modeling (FEM) is a numerical technique which is used to simulate and predict several aspects of behavior of a system. While FEM was applied by Xu *et al.* [11, 12] and Krabicka [13, 14] to optimize the circular electrode of electrostatic sensors, it cannot catch the optimal value of different physical characteristics of electrostatic sensors. All of these methods do not obtain an exact amount of different parameters of electrodes for electrostatic sensors. On the other hand, PSO has a few parameters to adjust in addition to easy implementation. Consequently, it is evident that PSO is more reliable to optimize the geometric sizes of several electrodes.

As be mentioned, until now, although so many researchers have studied on electrostatic sensors in several applications, the optimization of these sensors has significant issue. Therefore, PSO is applied as a new technique for optimizing these electrodes in this research. Then, several shapes of electrodes are applied in laboratory. Correlation velocity, mean particle velocity, and spatial sensitivity are experimentally calculated, thereafter. To verify the proposed method for optimization, experimental data are compared with optimization results. These results have a close agreement that shows PSO is a possible approach to apply for electrostatic sensor optimization.

2.0 RESEARCH METHODOLOGY

The measurement of velocity measurement and spatial sensitivity of various electrodes including circular- ring, quarter- ring, and rectangular will be examined. The optimization of geometric seizes of these electrodes is main aspect in this study.

Spatial sensitivity is defined as an absolute amount of induced charge. When the particles move downwards in a pipeline, a net electrostatic charge is generated because of particles collisions with each other and with the pipeline wall. The physical and chemical characteristics of particles influence on the amount of collisions. At first, these electrodes are designed and their spatial sensitivity equations are mathematically calculated. After that, particle swarm optimization technique is applied to obtain optimal value of different parameters. Then, several electrodes in different physical sizes are examined in laboratory to verify the optimization results. The flowchart of this research is depicted in Figure 1.

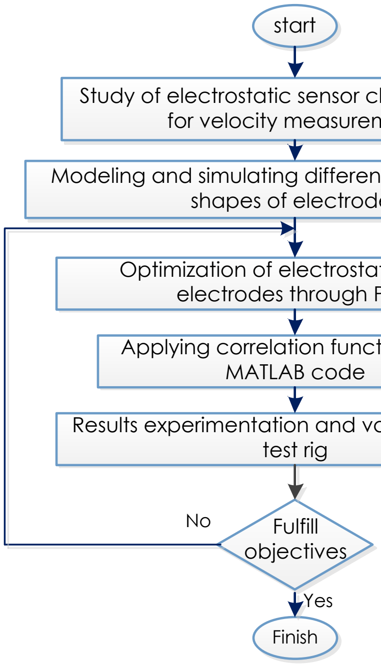


Figure 1 The flowchart of the algorithm for optimization of electrostatic sensor electrodes with the correlation method to measure the velocity

2.1 Mathmatical Model

As be mentioned earlier, three types of electrodes, circular- ring, quarter- ring and rectangular, are modeled and their mathematical equations are described[15]. Figure 2 shows the modeling of circular- ring-shaped electrode.

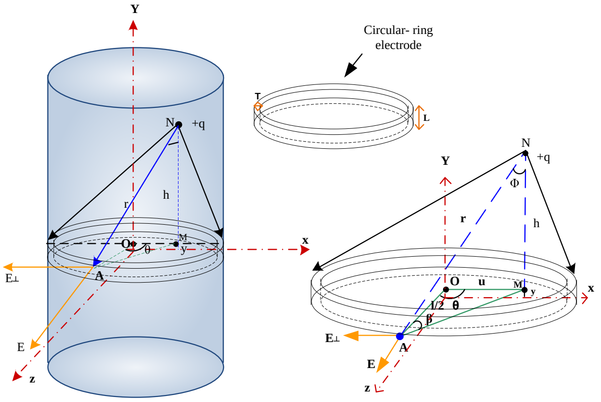


Figure 2 The modeling of circular- ring- shaped electrode

All of equations and derivations of several electrodes are mathematically calculated by Heydarianasl and Rahmat [16]. To summarize this section, only the final equations for induced charge and spatial sensitivity of these electrodes are stated in this paper.

The equation of induced charge, Q, and spatial sensitivity, S(u), for circular ring electrode are as following:

$$Q=-\frac{qr}{8\pi}\int_{0}^{2\pi}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{u^2\cos^2\theta-\left(2(y-h)^2+2u^2\right)+(r+0.5T)u\cos\theta}{\left[(y-h)^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r+0.5T)^2(y-h)^2+u^2-u(2r+T)\cos\theta\right]^{\frac{1}{2}}}-\frac{u^2\cos^2\theta-\left(2(y-h)^2+2u^2\right)+(r-0.5T)u\cos\theta}{\left[(y-h)^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r-0.5T)^2(y-h)^2+u^2-u(2r-T)\cos\theta\right]^{\frac{1}{2}}}\right)dy\,d\theta \tag{1}$$

$$S(u)=\frac{r}{8\pi}\int_{0}^{2\pi}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{u^2\cos^2\theta-\left(2y^2+2u^2\right)+(r+0.5T)u\cos\theta}{\left[y^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r+0.5T)^2y^2+u^2-u(2r+T)\cos\theta\right]^{\frac{1}{2}}}-\frac{u^2\cos^2\theta-\left(2y^2+2u^2\right)+(r-0.5T)u\cos\theta}{\left[y^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r-0.5T)^2y^2+u^2-u(2r-T)\cos\theta\right]^{\frac{1}{2}}}\right)dy\,d\theta \tag{2}$$

where h=v.t; v and t standing for the particle speed and time, respectively. L (length), W (width), T (thickness), and r (diameter) are the geometric parameters of the electrodes, while u denotes the specific axial position.

The model of quarter- ring electrode is depicted in Figure 3. Then, the equation of induced charge and spatial sensitivity of this electrode is described by equation (3), and (4), respectively.

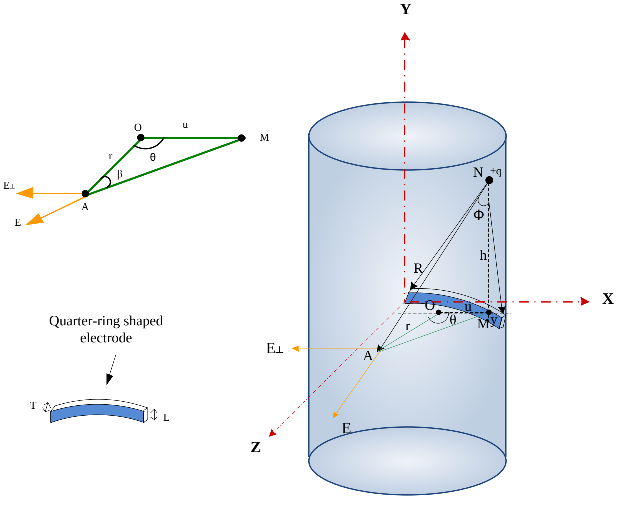


Figure 3 The modeling of quarter- ring- shaped electrode

$$Q=-\frac{qr}{8\pi}\int_{\frac{\pi}{6}}^{\frac{2\pi}{3}}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{u^2\cos^2\theta-\left(2(y-h)^2+2u^2\right)+(r+0.5T)u\cos\theta}{\left[(y-h)^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r+0.5T)^2(y-h)^2+u^2-u\ (2r+T)\cos\theta\right]^{\frac{1}{2}}}-\frac{u^2\cos^2\theta-\left(2(y-h)^2+2u^2\right)+(r-0.5T)u\cos\theta}{\left[(y-h)^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r-0.5T)^2(y-h)^2+u^2-u\ (2r-T)\cos\theta\right]^{\frac{1}{2}}}\right)dy\,d\theta \tag{3}$$

$$S(u)=\frac{r}{8\pi}\int_{\frac{\pi}{6}}^{\frac{2\pi}{3}}\int_{-\frac{L}{2}}^{\frac{L}{2}}\left(\frac{u^2\cos^2\theta-\left(2y^2+2u^2\right)+(r+0.5T)u\cos\theta}{\left[y^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r+0.5T)^2y^2+u^2-u\ (2r+T)\cos\theta\right]^{\frac{1}{2}}}-\frac{u^2\cos^2\theta-\left(2y^2+2u^2\right)+(r-0.5T)u\cos\theta}{\left[y^2+u^2-u^2\cos^2\theta\right]\cdot\left[(r-0.5T)^2y^2+u^2-u(2r-T)\cos\theta\right]^{\frac{1}{2}}}\right)dy\,d\theta \tag{4}$$

Finally, the rectangular electrode is modeled as is shown in Figure 4. Additionally, the formula of induced charge and spatial sensitivity of this electrode is calculated by (5), and (6), respectively.

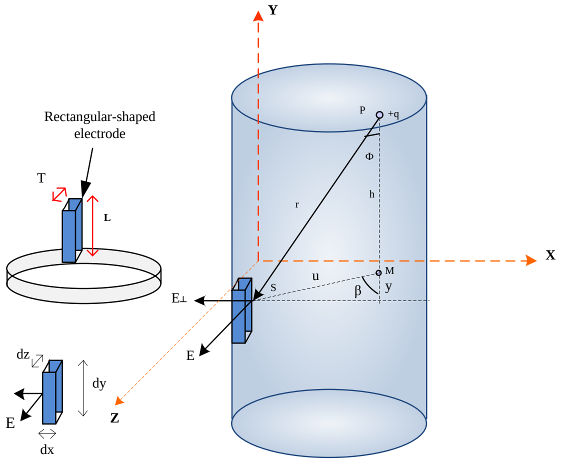


Figure 4 The modeling of rectangular- shaped electrode

$$Q=-\frac{q}{4\pi}\cdot\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_{-\frac{L}{2}}^{\frac{L}{2}}\frac{y}{\left((u-x)^2+(r-z)^2+h^2\right)^{\frac{3}{2}}}dy\,dx \tag{5}$$

$$S(u)=\frac{1}{4\pi}\cdot\int_{-\frac{W}{2}}^{\frac{W}{2}}\int_{-\frac{L}{2}}^{\frac{L}{2}}\frac{y}{\left((u-x)^2+(r-z)^2\right)^{\frac{3}{2}}}dy\,dx \tag{6}$$

The particular sensor output relates to numerous factors if a point charge conveying the sensor, which is often found simply by intended type. The specific axial place (u), particle speed (v), geometrical measurements of electrodes (T and also L) has considerable guideline around the sensor output. The thickness of electrodes has significant role on optimization that is ignored in previous researches. The particular mathematical model pertaining to these kinds of electrodes is recognized, and then, the equation of induced charge and also the spatial sensitivity of the electrodes are mathematically calculated. Mathematical model is required to obtain objective function for optimization method.

2.2 Optimization of Several Electrostatic Sensor Electrodes Using PSO Technique

PSO is a meta-heuristic technique to optimize a problem through repeat and improve a candidate solution corresponding to a given measure of quality. The basic theory of PSO algorithm is based on two formulas, velocity and position. These two equations are updated during the algorithm's implementation. These equations are stated as:

$$v_j(i+1) = w\,v_j(i) + c_1 r_1 \left(p_{best,j}(i) + x_j(i)\right) + \\ + c_2 r_2 \left(g_{best,j}(i) + x_j(i)\right) \quad (7)$$

$$x_j(i+1) = x_j(i) + v_j(i+1) \quad (8)$$

Where vj(i+1) and xj(i+1) denote the updated velocity and position, respectively. p_{best} indicate the best local particle position and g_{best} is the best global position. w describe the inertia weight function for PSO algorithm and it is important to control the velocity and to balance between local and global search position. r_1 and r_2 are the random number that are weighted between 0 and 1. Finally, c_1 and c_2, which are less than 2, denote the coefficient factors. To apply this method for electrostatic sensor electrodes, spatial sensitivity of electrode is defined as objective function that should be maximized. The equation of spatial sensitivity for several electrodes is calculated in section 2.1. Length and thickness of electrodes are considered as PSO parameters.

Figures 5 till 7 depict the results of PSO method to optimize the several electrostatic sensor electrodes. The right diagram in these Figures shows different position to search the best situation. The left diagram shows the Pareto front graph of thickness of electrode (x_2) with regard to the length of electrode (x_1). According to these graphs, Table 1 shows the best amount of thickness and length of various electrodes given by PSO technique. The results of circular- ring electrode are depicted in situation 1 and then they are compared with the results of quarter- ring and rectangular electrodes, which are shown in situations 2 and 3, respectively. The result of circular- ring electrode is more suitable than others since it has more amount of spatial sensitivity and the values of length and thickness of electrode is near the experimental results.

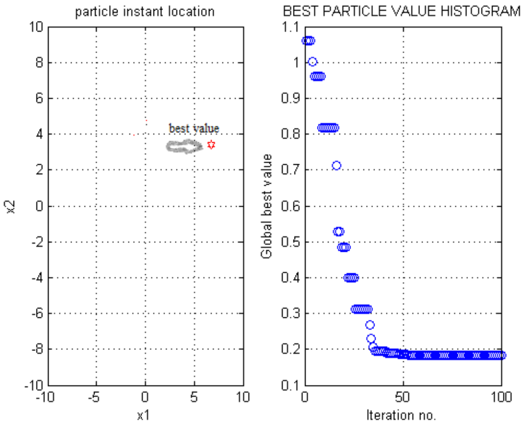


Figure 5 Optimization results of circular- ring- shaped electrode

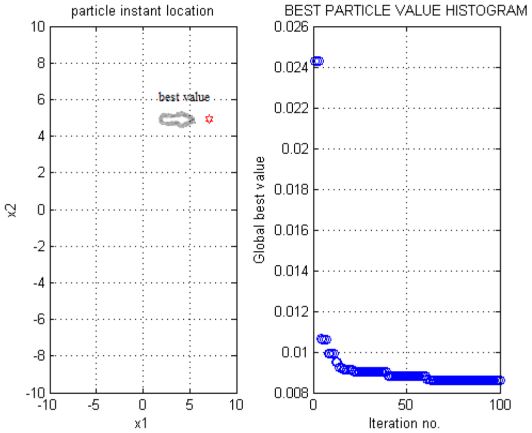


Figure 6 Optimization results of quarter- ring- shaped electrode

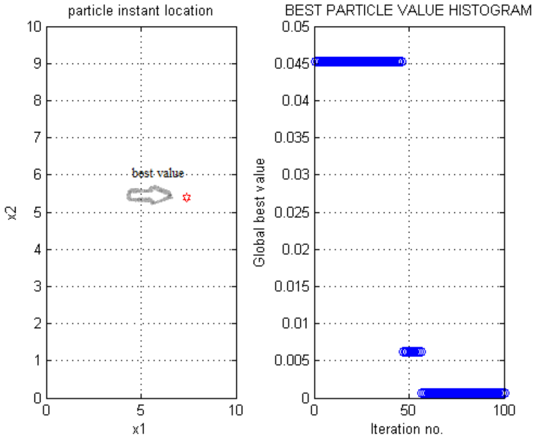


Figure 7 Optimization results of rectangular- shaped electrode

Table 1 Optimization results of several electrodes

Geometric parameters / Electrode Types	Length of electrode (mm)	Thickness of electrode (mm)	Spatial sensitivity (%)
Circular- ring	5.771	4.764	0.985
Quarter- ring	6.747	4.582	0.160
Rectangular	6.508	5.304	0.721

3.0 EXPERIMENTAL RESULTS

To compare the effect of geometric characteristics of electrodes on the sensing properties, several tests under different conditions are done in laboratory. The schematic of experimental test rig is shown in Figure 8. The correlation velocity, mean particle velocity, and spatial sensitivity are measured in laboratory since discrepancy between correlation velocity and mean particle velocity leads to non-uniform spatial sensitivity. The free fall velocity of solid particles is related to the height, h, from funnel to the center of electrode. If h equals to 80 cm, the free fall velocity is 3.996 m/s, which can be calculated by $(2gh)^{1/2}$. g represents the gravitational factor and equals to 9.98. To measure the correlation velocity, two electrostatic sensors are installed in different separations such as 5 cm, 10 cm, 15 cm, and 20 cm. And then, cross correlation method is applied. Cross correlation function and velocity is calculated by equations (9) and (10), respectively.

$$R_{xy}(\tau) = \frac{1}{T}\int_{0}^{T} x(t)\, y(t-\tau)\, dt \qquad (9)$$

$$V_C = \frac{D}{\tau_m} \qquad (10)$$

Where, $R_{xy}(\tau)$ is the cross correlation function, x(t) is the upstream signal and y(t) is the downstream signal, when the particle move down. τ shows the time lag between two sensors.

The correlation velocity of particles is shown by V_C, which depends on distance and the time delay between two sensors, as shown D and τ_m, respectively.

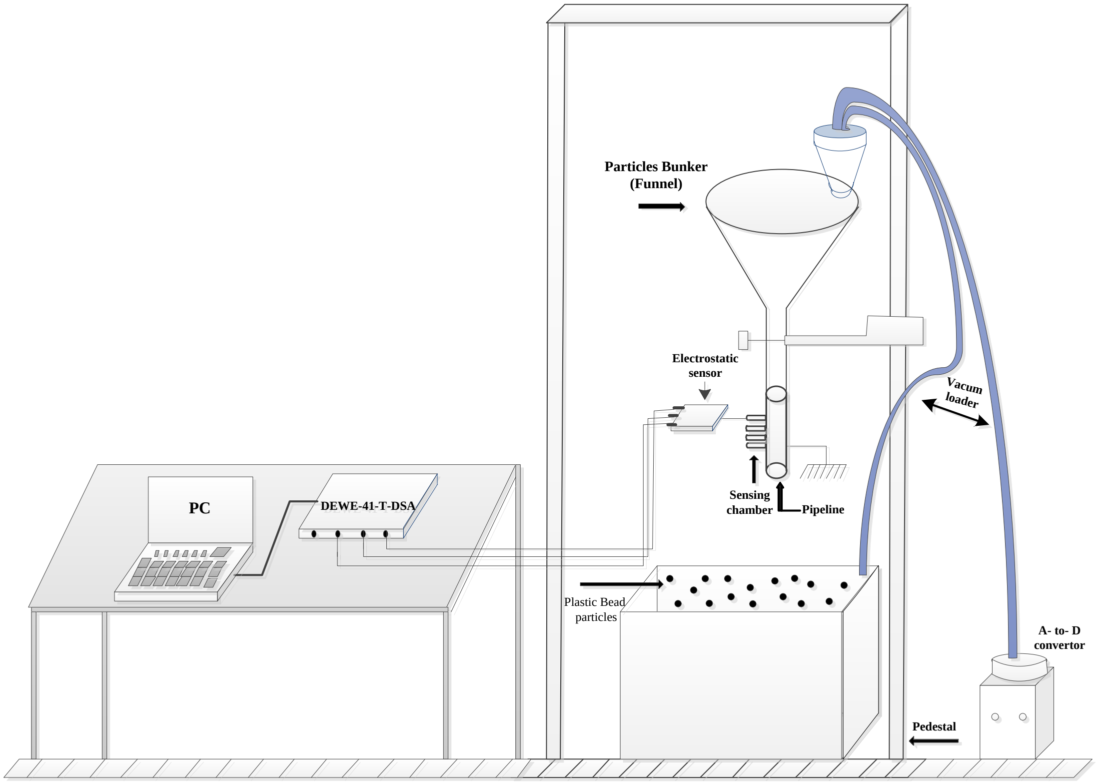


Figure 8 The schematic of experimental test rig

In this research, the correlation velocity of solid particle are measured through various types of electrodes including circular- ring, quarter- ring, and rectangular with different physical characteristics. Four values are considered for length of electrode (i.e. 3 mm, 6 mm, 10 mm, and 15 mm) and three amounts are examined for thickness of electrode (i.e. 2 mm, 5 mm, and 8 mm) in laboratory. The output signals of upstream and downstream sensors and their correlation diagram for several electrodes are shown in Figures 9 till 11. In these Figures, the length and thickness of electrodes are equal to 6 mm, and 5 mm, respectively. To summarize the results, the bar charts of correlation velocity are depicted in Figures 12 till 14. As is shown, increase the length and thickness of electrodes leads to decrease the correlation velocity and increase the difference between correlation and mean particle velocity. Hence, it causes to descend uniformity of spatial sensitivity. Figures 15 till 17 depict the bar chart of spatial sensitivity. It is evident that spatial sensitivity of electrode is ascended due to rise of these parameters. In general, longer length and thicker thickness of electrode leads to more uniform spatial sensitivity while they decrease the correlation velocity of solid particles. Analytically, consistency of spatial sensitivity is declined because of reduce the correlation velocity. Therefore, the best amount of length and thickness of electrode should be caught to achieve suitable value of correlation velocity in addition to more uniform spatial sensitivity. Corresponding to the experimentation, the best value of thickness and length of electrode is 5 mm, and 6 mm, respectively, as is shown in Table 2. In this condition, the difference between velocities is as less as possible while the uniformity of spatial sensitivity is kept.

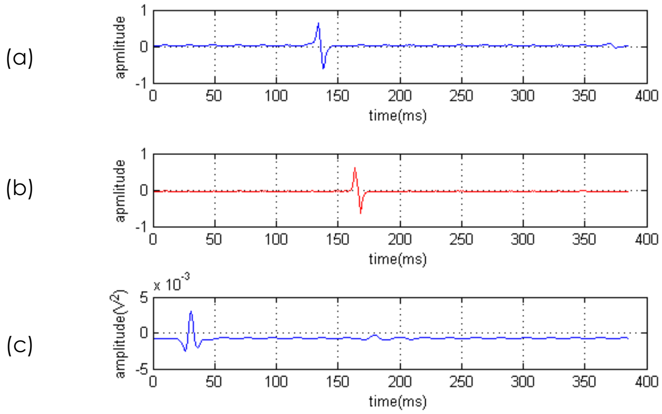


Figure 9 The output signals of circular- ring- shaped electrode for (a) upstream sensor (b) downstream sensor (c) correlation diagram; sampling frequency= 1000 Hz, D=15 cm, L=6 mm, T=5 mm

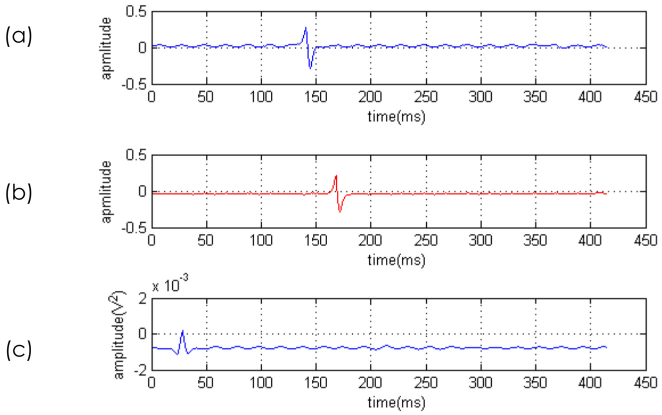


Figure 10 The output signals of quarter- ring- shaped electrode for (a) upstream sensor (b) downstream sensor (c) correlation diagram; sampling frequency= 1000 Hz, D=15 cm, L=6 mm, T=5 mm

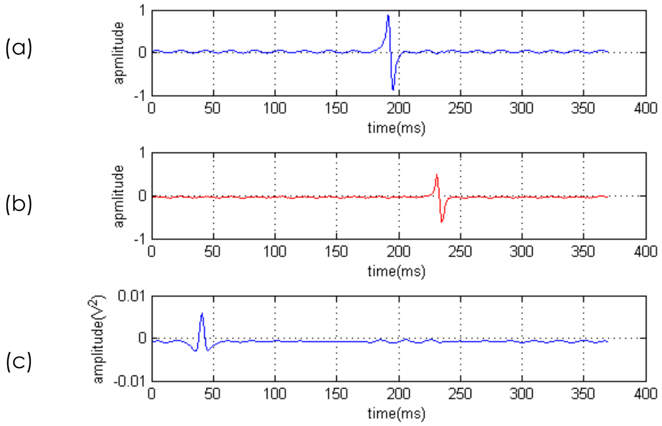


Figure 11 The output signals of rectangular- shaped electrode for (a) upstream sensor (b) downstream sensor (c) correlation diagram; sampling frequency= 1000 Hz, D=15 cm, L=6 mm, T=5 mm

Table 2 the best value of experimental results for several electrodes

Geometric parameters / Electrode Types	Length of electrode (mm)	Thickness of electrode (mm)	Spatial sensitivity (%)
Circular- ring	6.000	5.000	0.962
Quarter- ring	6.000	4.000	0.120
Rectangular	6.000	5.000	0.706

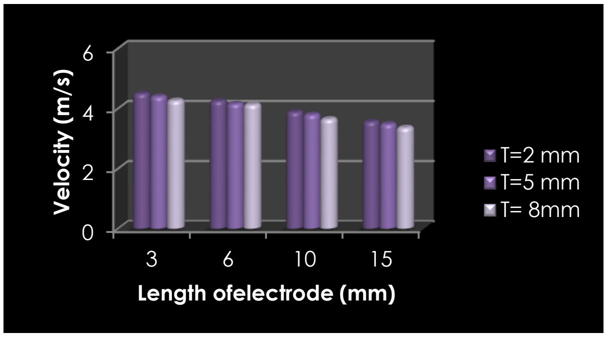


Figure 12 The bar- chart of correlation velocity of circular-ring- shaped electrode corresponding to experimental data

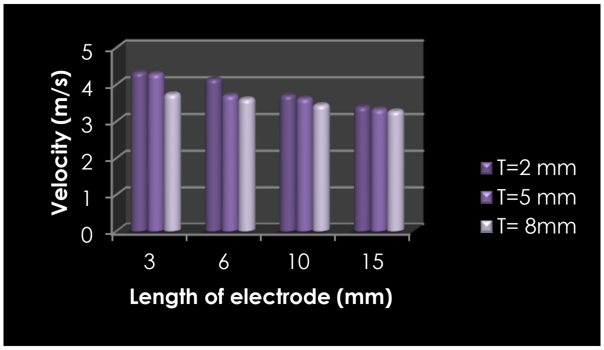


Figure 13 The bar- chart of correlation velocity of quarter-ring- shaped electrode corresponding to experimental data

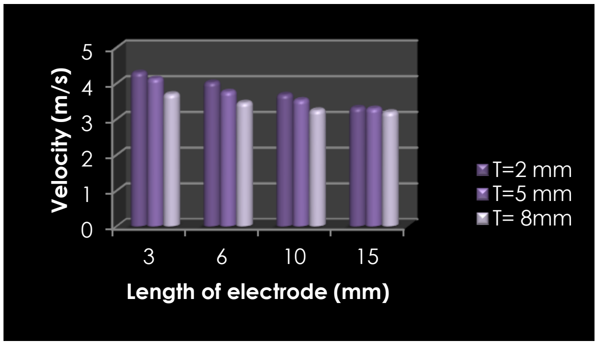


Figure 14 The bar- chart of correlation velocity of rectangular- shaped electrode corresponding to experimental data

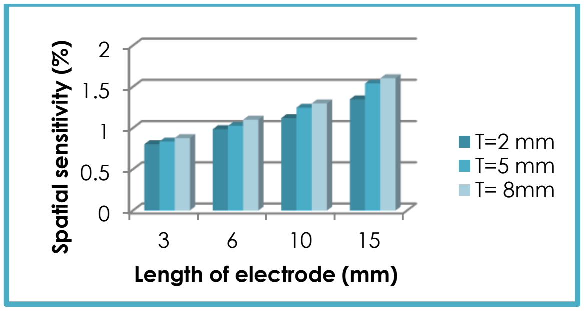


Figure 15 The bar- chart of spatial sensitivity of circular- ring-shaped electrode corresponding to experimental data

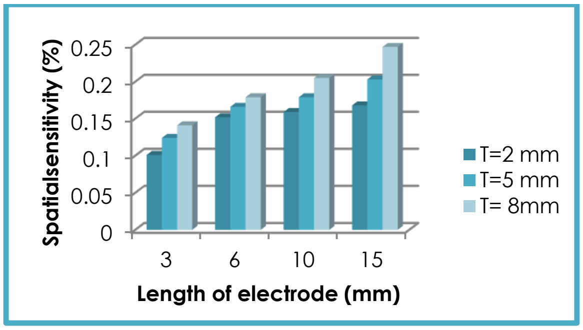


Figure 16 The bar- chart of spatial sensitivity of quarter- ring-shaped electrode corresponding to experimental data

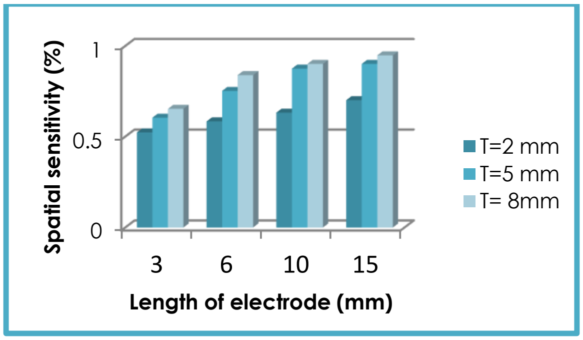


Figure 17 The bar- chart of spatial sensitivity of rectangular-shaped electrode corresponding to experimental data

4.0 RESULTS AND DISCUSSION

The validity of the proposed optimization method (PSO) is confirmed by comparison of experimental data with the analytical calculations. Application of the technique defined on a set of experimental data can compute the parameters based on a certain electrode.

First in the introduction, the design of the electrostatic sensors, in terms of the dimensions of its electrode, including its length and thickness was discussed. This was followed by an examination of the cross- sectional shape of the circular- ring, quarter- ring, and rectangular electrodes to ascertain which type was most appropriate. A method was applied to optimize different characteristics of electrodes. Then, a method was devised for the measurement of the mean velocity of particles from the output signal of an electrostatic sensor, and the result of the model were verified by the experimental data obtained through the use of DEWETRON (DEWE-41-T-DSA) data acquisition equipment in the test rig. Finally, experimental and optimization output signals are compared with each other.

Corresponding to optimization results, 3-D graphs of spatial sensitivity of different electrodes are depicted in Figures 18 till 20 and Figures 21 till 23 illustrate the 3-D graphs of spatial sensitivity according to experimentation. Comparison a pair of these graphs for each electrode reveal great agreement between optimization and experimental results, that it is assured applying of the PSO method to optimize several geometric sizes of electrodes for measuring the velocity of particles in pipeline. As be mentioned, physical characteristics of circular- ring, quarter-ring and rectangular electrodes were analyzed experimentally and mathematically in this paper. Furthermore, the results by optimization verify that shapes of electrodes influence on uniformity of spatial sensitivity. Therefore, circular- ring electrode is more suitable due to more uniform spatial sensitivity.

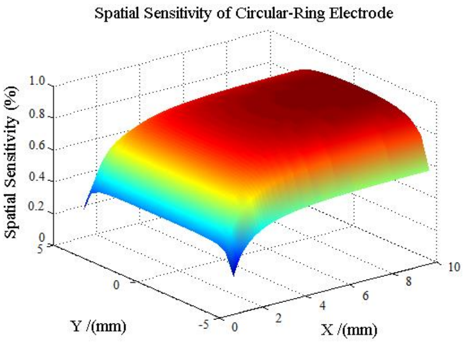


Figure 18 3-D graph of spatial sensitivity of circular- ring-shaped electrode according to optimization

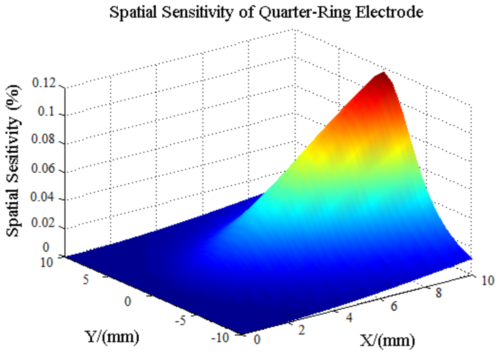


Figure 19 3-D graph of spatial sensitivity of quarter- ring-shaped electrode according to optimization

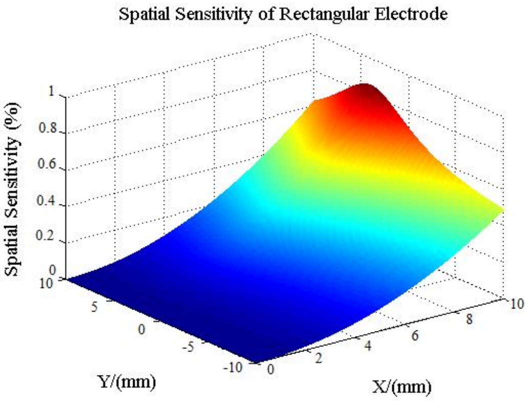


Figure 20 3-D graph of spatial sensitivity of rectangular-shaped electrode according to optimization

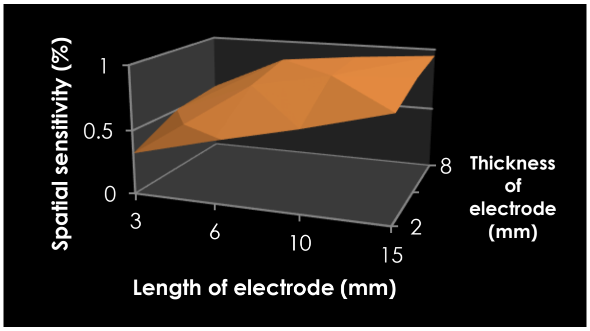


Figure 21 3-D graph of spatial sensitivity of circular- ring-shaped electrode corresponding to experimental data

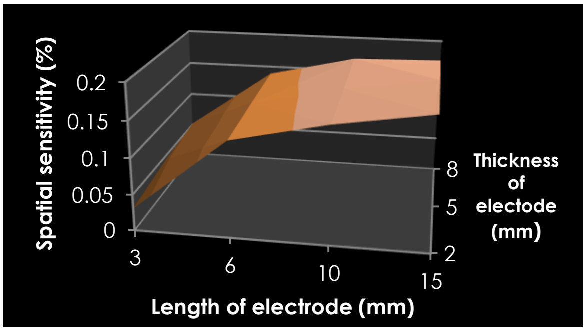


Figure 22 3-D graph of spatial sensitivity of quarter- ring-shaped electrode corresponding to experimental data

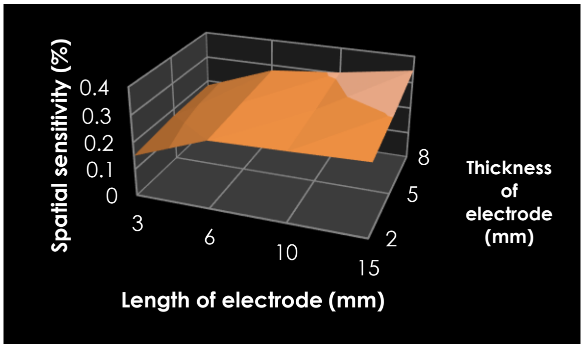


Figure 23 3-D graph of spatial sensitivity of rectangular-shaped electrode corresponding to experimental data

5.0 CONCLUSION

This paper discussed not only about the effects of several shapes of electrodes, including circular- ring, quarter- ring, and rectangular but also about the effects of different physical sizes of electrode to attain more uniform spatial sensitivity. To reduce the effect of flow regime, spatial sensitivity of electrodes need to be uniformed. Therefore, the PSO method is applied to optimize the physical characteristics and then maximized the spatial sensitivity. Various amounts of thickness and length of electrode are applied in laboratory and the correlation velocity of particle and spatial sensitivity are measured. It is obvious that the correlation velocity has proximate role on spatial sensitivity of electrodes. According to optimization results in Table 1, the optimal value of thickness and length of circular- ring electrode is 4.764 mm and 5.771 mm, respectively. Additionally, the results of experimentation show that the best amount of thickness and length of electrode, to reach the maximum similarity between correlation velocity and mean particle velocity and to attain more uniform spatial sensitivity, is 5 mm and 6 mm, respectively. It is clearly evident that, PSO method is feasible to optimize the electrode designs. Moreover, according to optimization and experimental data, the diagram of spatial sensitivity for circular- ring electrode is more consistent. Hence, the circular- ring electrode with 5 mm thickness and 6 mm length is suggested to apply in numerous industries.

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