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The Effects of Distance on Velocity Measurement for Different Shapes of Electrostatic Sensor Electrodes

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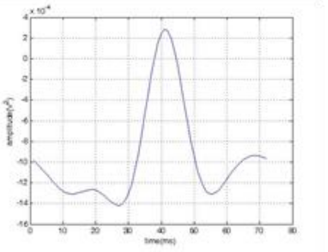
Graphical abstract



Abstract

Velocity measurement has significant role in several industries that cope with particles to sa consumption and to improve quality of particles. This paper describes the effect of distance on vel measurement for different shapes of electrodes for example pin, circular, rectangular, and qu electrode. This distance is referred to separation of electrodes. Electrostatic sensors are suitab measure the velocity of particles due to their inexpensive, simplicity and robust. These shapes electrodes are modeled by mathematical equations and analyzed by Mathcad software. In velocity is measured in laboratory by different shapes of electrodes in different distances. C correlation method is experimentally used to measure the velocity. Increase the distance between electrodes leads to increase the time lag, but velocity remains constant. The results of modeling electro and experimental tests are compared with each other and they verify that these electrodes a reliable in industries in addition to cost-effectiveness and high efficiency.

Keywords: Velocity measurement; cross correlation method; electrostatic sensors; circular electrode; p electrode

1.0 INTRODUCTION

Among numerous applications of velocity measurement, such as to measure the robot velocity and to be used in the industries that deal with powder or biomass and coal, the significant role of it is to manage and to monitor particles manner using electrostatic sensors, which are used due to their proficiency of providing dependable velocity in pneumatic conveying solid particles with exceptional repeatability and reckless dynamic reaction under an industrial situation.

Electrostatic sensors are used to monitor the flow of particle since the early 1980s [1-3] and they have gradually improved. Nowadays, electrostatic sensors have been attracted to using in various industries because they are inherently vigorous and profitable. These sensors have distinct types of cross sectional shaped of the electrodes, such as ring, pin, quarter-ring and rectangular, as are shown in Figure 1, which each of them has different characteristics. This paper only focuses on circular and pin electrodes and their results for measuring velocity are compared with one another. These electrodes are briefly described. The most mutual and investigated electrode type is the non-intrusive ring which is solely a reedy round electrode that shape part of the pipeline wall but is electrically protected from it. Circular or ring shape of electrode is normally embedded in the Pipeline wall via insulator which this is defined the non-intrusive arrangement. Circular electrodes of electrostatic sensors have more researched while so many problems are suffered by them. Ring electrodes usually shape of a reel part mounted in line with the rest of the pipeline that requires elimination of a section of pipeline and insertion of the reel part. Hence, this kind of connection has parameters like difficulty, costly, and often impractical for large pipeline in troublesome positions. While circular electrodes have a weak answer to flow circumstances near the pipeline center, they have most sensitive to particles near the pipeline wall.

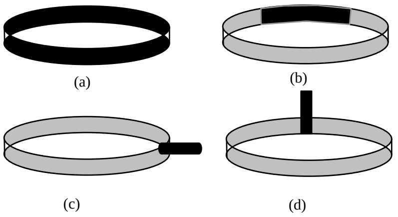


Figure 1 Different cross sectional shapes of electrodes including (a) circular electrode, (b) quarter-ring electrode, (c)pin electrode, (d) rectangular electrode

In contrast, another kind of electrode of electrostatic sensor is rod electrode. In this case, the rod or pin electrode protrudes into the pipeline vertical to the pipeline wall. This type of electrodes is called intrusive electrodes that are much easier to mount and just necessitate an appropriate hole drilled into an expedient unit of pipeline. Intrusive electrode may be covered with an exceptional material due to a harsh native of the particle flow [4-6]. These electrodes must be covered with the singular material to ascend their robustness. The sensitivity in pin electrodes like ring electrodes is based on the area directly next to the electrode.

The rod shape probe has benefits of high sensitivity and can obtain the overall information of charged particles flow in its sensitive zone considering the precise layout and installation of the probe, and the operation safety of the dense phase pneumatic conveying system under high pressure and other electrostatic probe was adopted [7-8]. Intrusive electrostatic sensors for the velocity measurement of pneumatically conveyed particles have been examined in this research.

In addition, there are different methods for velocity measurement; such as cross correlation that observe similarities between two output signals, downstream and upstream. Xu in 1998; [9] Beck in 1981 [1] and 1987 [2]; and Yan in 1996 [10] argued about cross correlation flow measurement technique. They told this method is applicable to use in industry and laboratory pipelines. Besides, S.R. Woodhead *et al.* in 1995 [11] represented the principle of electrostatic correlation signal processing approach and the test facility. In addition, the cross correlation and laser Doppler Velocimetery results compared one another. Then, W.Q. Yang and M.S. Beck in 1998 [12] put forward a new intelligent cross correlator that added an auto frequency function its software. Y. Yan *et al.* in 2006 [13] explained more about this correlator and the criterion used for sampling frequency selection that is strongly influenced by the frequency characteristic of the signal.

Cross correlation method include two sensors in upstream and downstream of pipeline. Particles move between these two sensors. The distance of them is significant and influence on correlation coefficient as well as velocity. The movement particles create a net electrostatic charge, from interaction between particles in addition particle and wall of pipeline. Figure 2 illustrates the schematic of cross correlation method to measure the velocity.

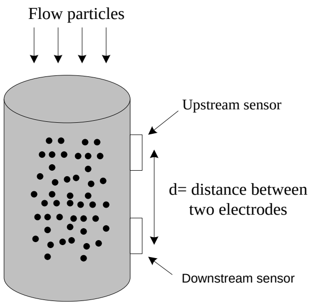


Figure 2 Schematic of cross correlation method to measure the velocity

2.0 METHODOLOGY

In this study, the measurement of velocity using intrusive electrostatic sensors will examine particle flow in a pneumatic conveying pipeline. The movement of particulate materials in a pneumatic pipeline produces a net electrostatic charge on the particles through interaction between the particles, with the pipeline and the conveying air. The volume of interaction is dependent on a variety of features, such as the immediate environment in the pipeline, and the chemical and physical properties of the particles. Mathematical modelling and experimental tests are required to calculate the sensing features and to analyse the fundamental interaction between the charged particles and the sensor.

2.1 Mathmatical Model

Different types of electrodes, circular, quarter-ring, pin, and rectangular are modeled and their mathematical equations are described [14]. Figure 3 shows the modeling of circular-shaped electrode.

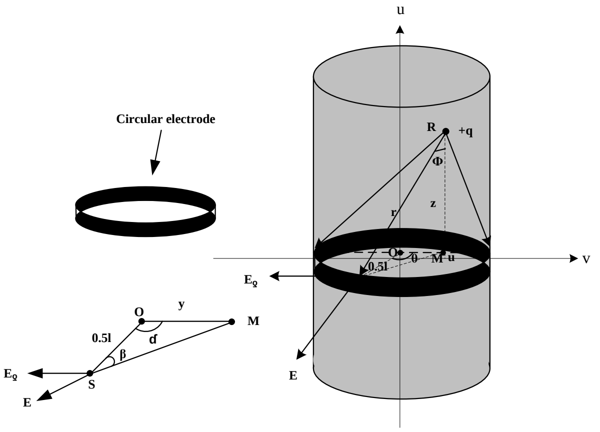


Figure 3 Modeling of circular- shaped electrode

The induced charge, Q, on the electrode depends on the charge density, σ, on the inner surface of the electrode; the following equation shows the relationship between them:

$$Q=\oint_{S} \sigma \, .ds \tag{1}$$

Electrostatic theory states that the charge density on the inner surface of the electrode is same to the electric flux density, D;

$$D=\sigma \tag{2}$$

In addition, electrical field, E, is equal to:

$$D=\varepsilon_0 E \tag{3}$$

Therefore, with substituting (2) in (3), the surface charge density is calculated by:

$$\sigma=\varepsilon_0 E \tag{4}$$

Where ε_0 is the relative permittivity. Furthermore, the point charge, q, leads to the electrostatic field at the point S, which is shown in next equation:

$$E=\frac{q}{4\pi\varepsilon_0 r^2}=\frac{q}{4\pi\varepsilon_0 |RS|^2} \tag{5}$$

$$E\wedge=E\sin\phi\cos\beta \tag{6}$$

Where,

$$\sin\varphi = \frac{|MS|}{|RS|} \tag{7}$$

$$\cos\beta = \frac{(0.5l)^2 + (MS)^2 - y^2}{l(MS)} \tag{8}$$

Hence,

$$E_\perp = E \cdot \frac{|MS|}{|RS|} \cdot \frac{(0.5l^2) + (MS)^2 - y^2}{l(MS)} \tag{9}$$

where,

$$|RS| = \sqrt{|MS|^2 + |RM|^2} \tag{10}$$

$$|MS| = y^2 + (0.5l)^2 - (ly\cos\theta) \tag{11}$$

$$|RM| = (z-u) \tag{12}$$

With substituting from (9) to (12);

$$E_\perp = \frac{q}{4\pi\varepsilon_0 (RS)^2} \cdot \frac{(0.5l)^2 + y^2 + (0.5l)^2 - (ly\cos\theta) - y^2}{(RS)} \tag{13}$$

Finally,

$$E_\perp = \frac{q}{4\pi\varepsilon_0} \cdot \frac{(0.5l - y\cos\theta)}{\left(\left(y^2 + (0.5l)^2 - (ly\cos\theta)\right) + (z-u)^2\right)^{\frac{3}{2}}}$$

(14)

To simplify the analysis, the electrostatic field due to the point charge is estimated as the normalized electric field; consequently:

$$dQ = -\varepsilon_0 E d_S \Rightarrow dQ = -2\varepsilon_0 E_\perp d_S \tag{15}$$

$$d_S = \frac{1}{2} l \, du \, d\theta \tag{16}$$

$$dQ = -\varepsilon_0 \cdot \frac{q}{4\pi\varepsilon_0} \cdot \frac{(0.5l - y\cos\theta)}{\left(\left(y^2 + (0.5l)^2 - (ly\cos\theta)\right) + (z-u)^2\right)^{\frac{3}{2}}} \cdot \left(\frac{1}{2} l \, du \, d\theta\right)$$

(17)

$$Q = -\frac{ql}{4\pi} \int_0^{2\pi} \frac{(0.5l - y\cos\theta)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta)\right)} \cdot \left(\frac{(z+0.5w)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta) + (z+0.5w)^2\right)^{\frac{1}{2}}} - \frac{(z-0.5w)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta) + (z-0.5w)^2\right)^{\frac{1}{2}}} \right) d\theta$$

(18)

The actual current output of electrodes can be calculated while $z = v \cdot t$;

$$I(t) = \frac{dQ}{dt} = -\frac{qlv}{4\pi} \int_0^{2\pi} \frac{(0.5l - y\cos\theta)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta)\right)} \cdot \left(\frac{(z+0.5w)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta) + (z+0.5w)^2\right)^{\frac{1}{2}}} - \frac{(z-0.5w)}{\left(y^2 + (0.5l)^2 - (ly\cos\theta) + (z-0.5w)^2\right)^{\frac{1}{2}}} \right) d\theta$$

(19)

The particular sensor output relates to numerous factors if a point charge conveying the particular sensor, which is often found simply by intended type. The particular axial place (y), particle speed (v), geometrical measurements of electrodes (d and also l) has considerable guideline around the sensor output. To simplify modeling thickness of electrodes is ignored. The particular mathematical amount pertaining to these kinds of factors is recognized as, and then, the whole induced charge and also the current output of the electrodes will be determined simply by Mathcad computer software. The particular outputs for circular electrode are shown in Figures 4 and 5.

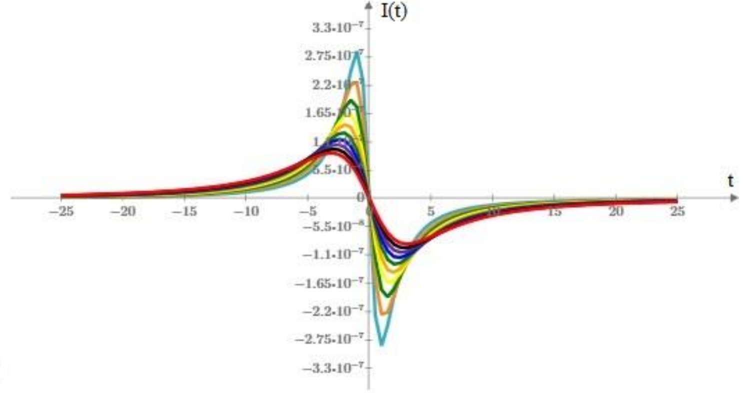


Figure 4 Current of circular-shaped electrode in different distance

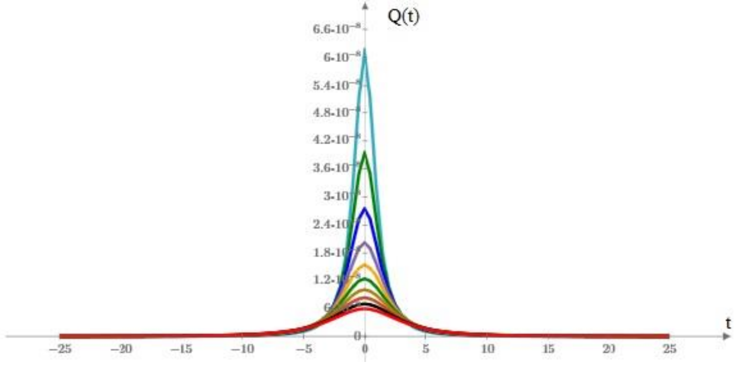


Figure 5 Induced charge of circular-shaped electrode in different distance

Quarter- ring electrode is the second type of electrodes, the modeling of this electrode is shown in Figure 6.

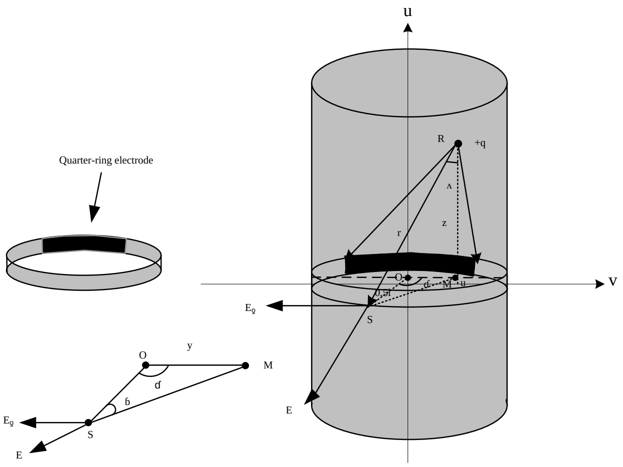


Figure 6 Modeling of quarter- ring shaped electrode

Quarter-ring electrode is similar to circular electrode with this difference that, $\frac{\pi}{6} \le \theta \le \frac{5\pi}{3}$. Consequently, the induced charge can be calculated by (20):

$$Q = -\frac{ql}{4\pi}\int_{\frac{\pi}{6}}^{\frac{2\pi}{3}} \frac{(0.5l - y\cos\theta)}{\left(y^2+(0.5l)^2-(ly\cos\theta)\right)} \cdot \left(\frac{(z+0.5w)}{\left(y^2+(0.5l)^2-(ly\cos\theta)+(z+0.5w)^2\right)^{\frac{1}{2}}} - \frac{(z-0.5w)}{\left(y^2+(0.5l)^2-(ly\cos\theta)+(z-0.5w)^2\right)^{\frac{1}{2}}}\right) d\theta \tag{20}$$

And the total actual current is equal to while z=v.t

$$I(t) = \frac{dQ}{dt} = -\frac{qlv}{4\pi}\int_{\frac{\pi}{6}}^{\frac{2\pi}{3}} \frac{(0.5l - y\cos\theta)}{\left(y^2+(0.5l)^2-(ly\cos\theta)\right)} \cdot \left(\frac{(z+0.5w)}{\left(y^2+(0.5l)^2-(ly\cos\theta)+(z+0.5w)^2\right)^{\frac{1}{2}}} - \frac{(z-0.5w)}{\left(y^2+(0.5l)^2-(ly\cos\theta)+(z-0.5w)^2\right)^{\frac{1}{2}}}\right) d\theta \tag{21}$$

The particular outputs of quarter-ring-shaped electrode, total current and induced charge, are shown in Figure 7 and 8.

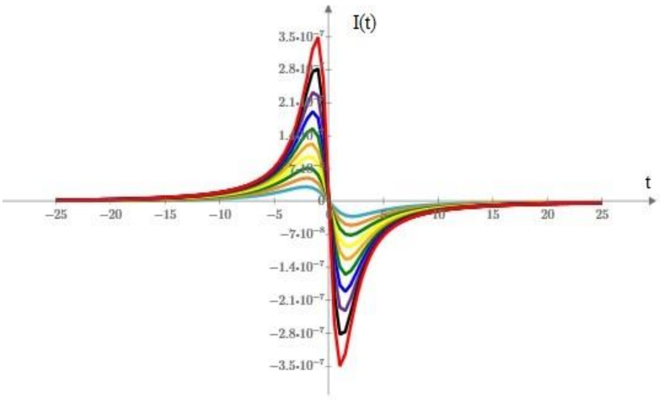


Figure 7 Current of quarter-ring shaped electrode in different distance

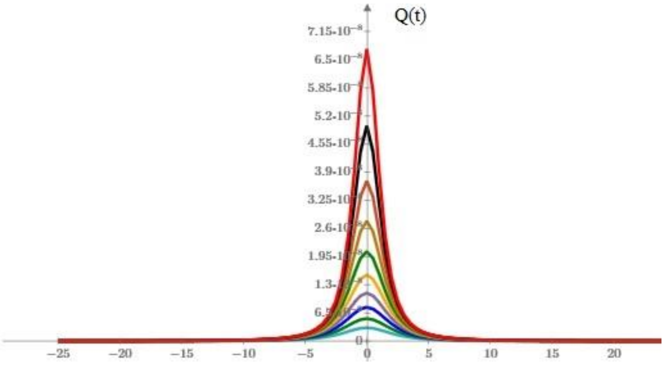


Figure 8 Induced charge of quarter-ring shaped electrode in different distance

Another type of electrode, which is taken into account in this research, is pin electrode. The model of pin electrode is shown in Figure 9 and following equations analyze the model.

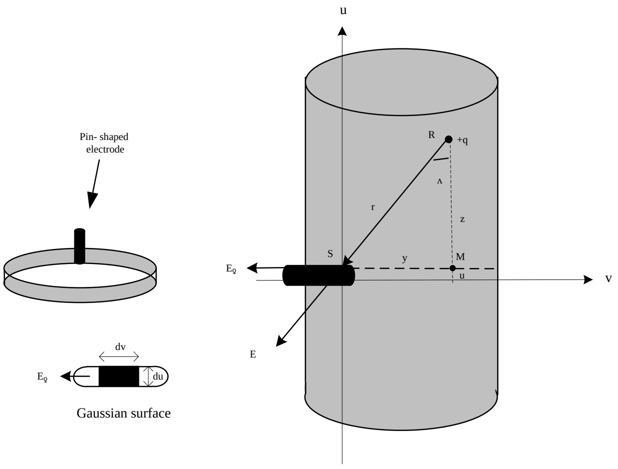


Figure 9 Modeling of pin-shaped electrode

The electrical field can be defined similar to circular-shaped electrode, as equation (5), but the normalized electrical field for this model is described by:

$$E_\perp = E\sin\theta \tag{22}$$

Where,

$$\sin\theta = \frac{|MS|}{|RS|} = \frac{y}{|RS|} \tag{23}$$

And,

$$|RS| = \sqrt{(z-u)^2+y^2} \tag{24}$$

Therefore, with substituting:

$$E_\perp = \frac{q}{4\pi\varepsilon_0} \cdot \frac{y}{\left((z-u)^2+y^2\right)^{\frac{3}{2}}} \tag{25}$$

$$dQ = -\varepsilon_0 E_\perp d_s \tag{26}$$

$$d_S = 2\pi\,\Delta u\,\Delta v \tag{27}$$

$$dQ = -\varepsilon_0 \cdot \frac{q}{4\pi\varepsilon_0} \cdot \frac{y}{\left((z-u)^2+y^2\right)^{\frac{3}{2}}} \cdot (2\pi\,\Delta u\,\Delta v) \tag{28}$$

Hence, the induced charge for pin-shaped electrode can be defined by:

$$Q(t) = -\frac{qd}{2}\int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{y}{\left((z-u)^2+y^2\right)^{\frac{3}{2}}}\,du \tag{29}$$

Where l and d, are the length and diameter of the electrode, respectively.

$$z = v.t \tag{30}$$

Finally, the total current of this model is calculated by following equation:

$$I(t)=\frac{dQ(t)}{dt}=-\frac{3qyvd}{2}\int_{-\frac{w}{2}}^{\frac{w}{2}}\frac{(u-z)}{\left((u-z)^2+y^2\right)^{\frac{5}{2}}}du \tag{31}$$

The output signals, including induced charge and total current, are shown in Figures 10 and 11.

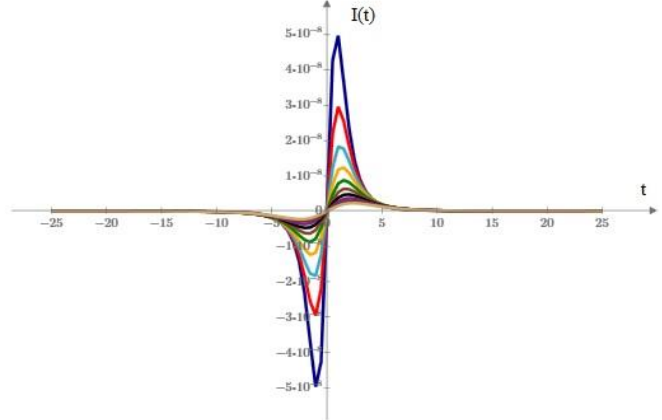


Figure 10 Current of pin- shaped electrode in different distance

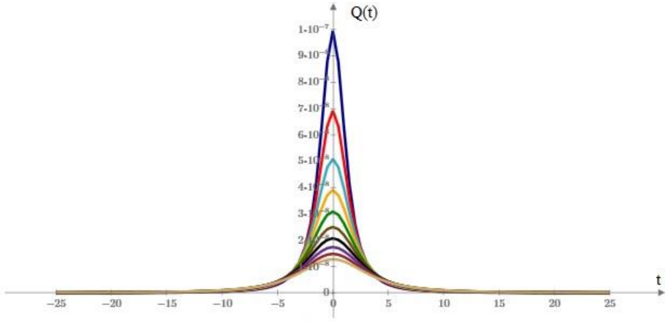


Figure 11 Induced charge of pin- shaped electrode in different distance

As be mentioned, rectangular shaped electrode is another kind of electrode for electrostatic sensor. The model of this electrode is shown in Figure 12 then is modeled by mathematical equations.

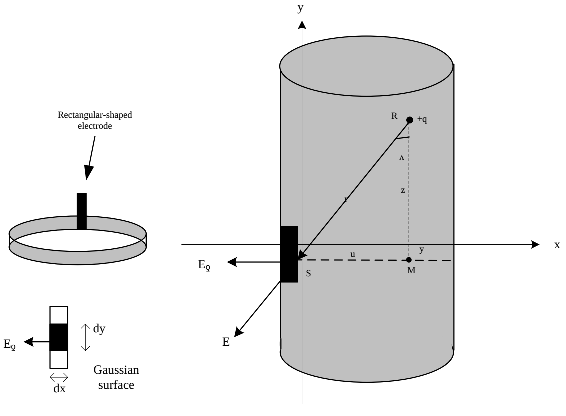


Figure 12 Modeling of rectangular- shaped electrode

Generally, electrostatic field and also normalized electrostatic field for this model are calculated by (32) and (33), respectively.

$$E=\frac{q}{4\pi\varepsilon_0 r^2}=\frac{q}{4\pi\varepsilon_0|RS|^2} \tag{32}$$

$$E_{\wedge}=E\sin\theta \tag{33}$$

The requirement parameters can be calculated by given model:

$$\sin\theta=\frac{|MS|}{|RS|}=\frac{u}{|RS|} \tag{34}$$

$$|RS|=\sqrt{(z+y)^2+u^2} \tag{35}$$

Hence, normalized electrostatic field can be calculated by following equation:

$$E_{\wedge}=\frac{q}{4\pi\varepsilon_0}\times\frac{u}{\left((z+y)^2+u^2\right)^{\frac{3}{2}}} \tag{36}$$

According to Guassian theory induced charge equals to:

$$dQ=-\varepsilon_0 E_{\wedge} d_s \tag{37}$$

And Guassian surface for this model is:

$$d_S=\Delta x\,\Delta y \tag{38}$$

Finally, total current and induced charge of this model can be calculated by (39) and (40) and their graph is shown in Figures 13 and 14, respectively.

$$Q(t)=-\frac{q\,w}{4\pi}\int_{-\frac{l}{2}}^{\frac{l}{2}}\frac{u}{\left((z+y)^2+u^2\right)^{\frac{3}{2}}}\,dy \tag{39}$$

$$I(t)=\frac{dQ(t)}{dt}=-\frac{3quvw}{4\pi}\int_{-\frac{l}{2}}^{\frac{l}{2}}\frac{(y+z)}{\left((y+z)^2+u^2\right)^{\frac{5}{2}}}dy \tag{40}$$

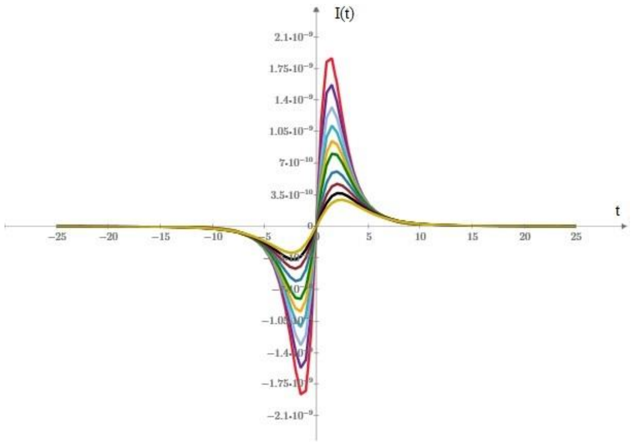


Figure 13 Current of rectangular- shaped electrode in different distance

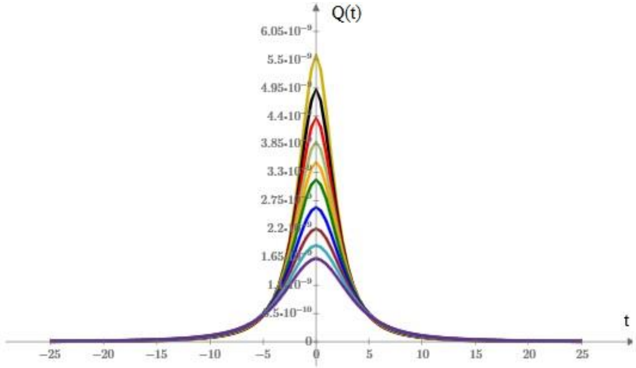


Figure 14 Induced charge of rectangular- shaped electrode in different distance

Mathematical model verify similarity between Output signals of different shapes of electrodes and shows the affect of distance on them. When the distance is small, the amplitude is high and the graph is sharper. With increasing the distance, the graph is wider.

2.2 Experimental Results

After modeling of different electrodes, they are examined in laboratory and velocity measurement of them is calculated using cross correlation method. This method compares similarities between upstream and downstream signals of electrodes by Matlab computer software. Cross correlation function and velocity are calculated by equations (41) and (42), respectively. The results of tests are shown in following figures and also tables.

$$R_{xy}(t)=\frac{1}{T}\int_0^T x(t)\,y(t-t)\,dt \qquad (41)$$

$$V=\frac{L}{t_m} \qquad (42)$$

Where, R_{xy}(Ű) is the cross correlation function, x(t) is the upstream signal and y(t) is the downstream signal, when the particle move down. Ű shows the time lag between The mean velocity of particles is shown by V, which depends on distance and the time delay between two sensors, as shown L and $Ű_m$, respectively.

As be mentioned, distance is a main factor for velocity measurement. This distance is referred to the length between upstream and downstream of the electrostatic sensors. Four distances under investigation are 5cm, 10cm, 15cm, and 20cm. A laboratory setup is constructed to measure the velocity of particles in these different distances. Electrostatic sensor is used in this study that is shown in Figure 15. Electrostatic sensor is used to monitor the particles flow in pipeline after that data acquisition system that is shown in Figure 16 is used to convert the output voltage from the sensor to computer codes, which provides data of velocity. Sensing sensor has three different outputs. Output 1 is used to amplify AC voltage signal or induced charge signal from electrode. Output 2 is used to rectify voltage of output 1 and also it is defined as sensor current signal. Output 3 is a low pass filter and shows the average voltage signal. The output 1 or non-inverting amplifier voltage is used for cross correlation measurement hence it is used in this research and shows the upstream or downstream signals. The model of data acquisition system used in this study is DEWE-41-T-DSA. This device with its related computer software DEWEsoft is used to capture the signals from the electrostatic sensors and examine them to numerical data then it computes the time lag of particles move between upstream to downstream electrodes. This device has four simultaneously sampled analog inputs and one tachometer input with 24-bit resolution and 102 dB dynamic ranges. Therefore, it is outstanding choice when a few inputs required for analysis and measurement. The maximum sampling rate for this device is 52 KS/s and the input range is between ±1 to ±10 V. It is powered by USB 2.0 port and does not need the additional power supply. A random plastic bead particles drop from hopper using gravity flow rig, as is shown in Figure 17. Therefore, there is not any issue of position relative to sensors.

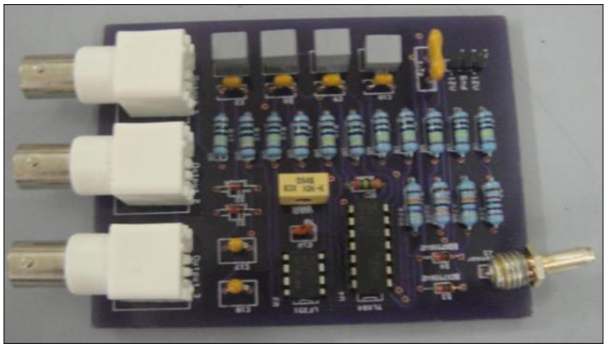


Figure 15 Electrostatic sensor used in laboratory

Figure 16 Data acquisition system

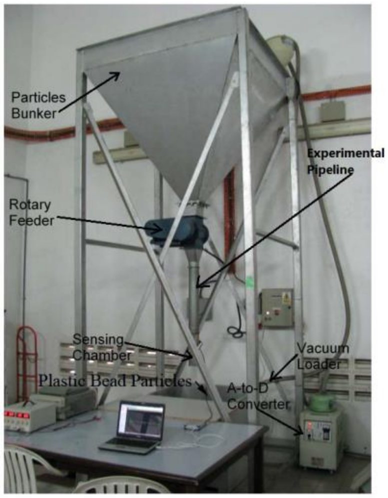
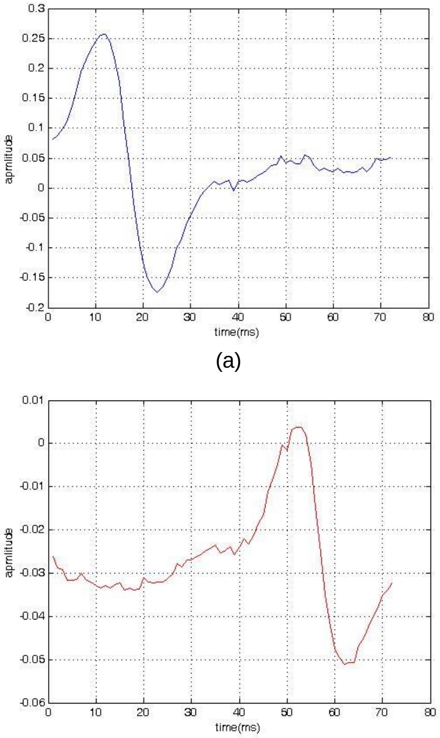


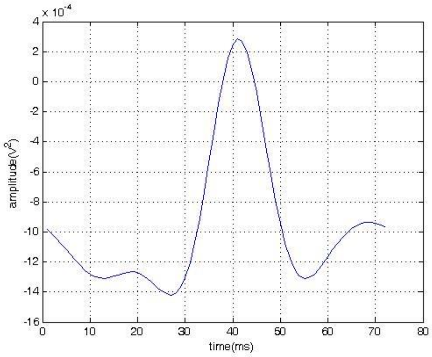
Figure 17 System in laboratory

The upstream and downstream signal and also cross correlation curve of different electrodes in distance and sampling frequency equal to 15 cm and 1 KHz, respectively, are shown in Figures 18-21. Tables 1-4 show the amount of velocity in different distance by different electrodes.



(a)

(b)

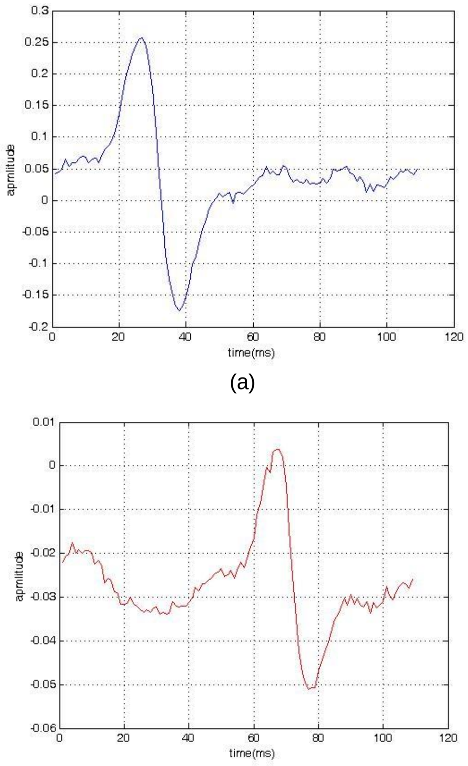


(c)

Figure 18 (a) Upstream signal, (b) Downstream signal, and (c) Cross correlation function of circular-shaped electrode in distance=15 cm, sampling frequency= 1 KHz

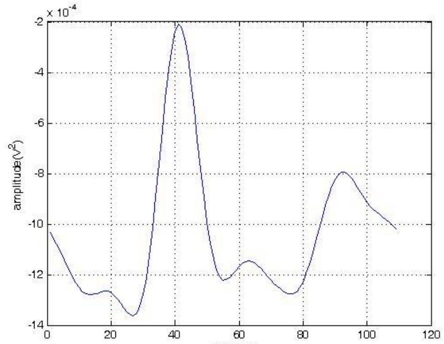
Table 1 Experimental results of circular- shaped electrode in sampling frequency= 1 KHz

Distance (cm)	Correlogram peak(v)	Time lag (ms)	Velocity (m/s)
5	0.0012	16	3.125
10	0.0135	29	3.4482
15	2.8510e4	41	3.6585
20	-5.6031e4	54	3.7037



(a)

(b)

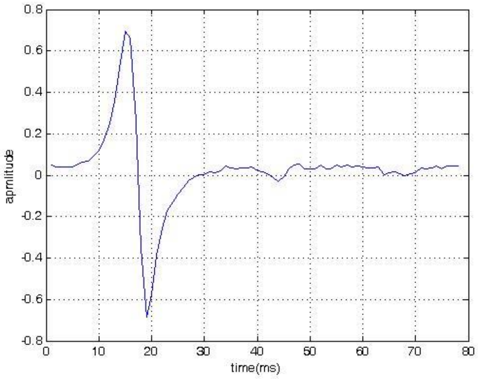


(c)

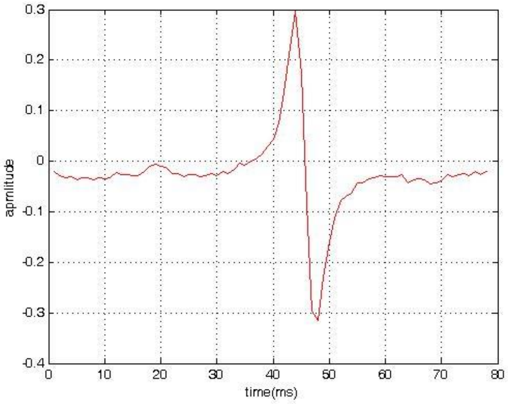
Figure 19 (a) Upstream signal, (b) Downstream signal, and (c) Cross correlation function of quarter- ring- shaped electrode in distance=15 cm, sampling frequency= 1 KHz

Table 2 Experimental results of quarter- ring- shaped electrode in sampling frequency= 1 KHz

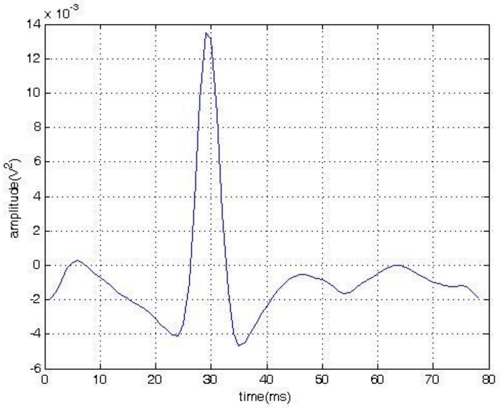
Distance (cm)	Correlogram peak(v)	Time lag (ms)	Velocity (m/s)
5	0.0303	16	3.125
10	0.0136	31	3.2258
15	-0.0020	45	3.3333
20	-0.0013	52	3.8461



(a)



(b)

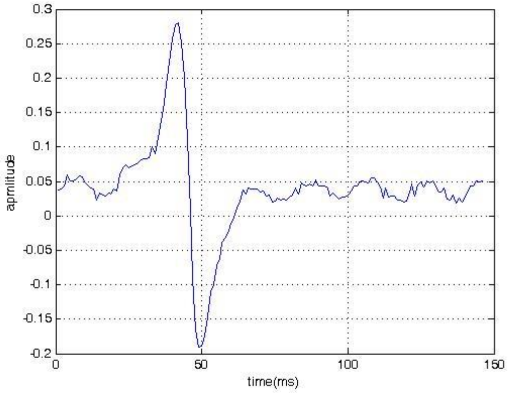


(c)

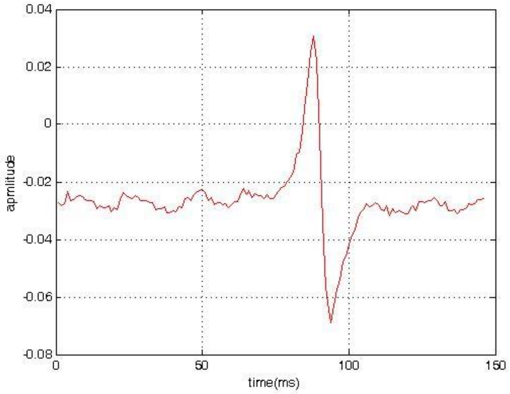
Figure 20 (a) Upstream signal, (b) Downstream signal, and (c) Cross correlation function of pin- shaped electrode in distance=15cm, sampling frequency= 1 KHz

Table 3 Experimental results of pin- shaped electrode in sampling frequency= 1 KHz

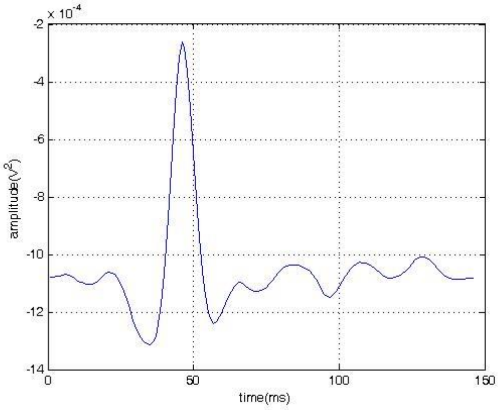
Distance (cm)	Correlogram peak(v)	Time lag (ms)	Velocity (m/s)
5	0.024	16	3.125
10	0.0212	31	3.2258
15	0.0035	45	3.3333
20	0.0033	52	3.8461



(a)



(b)



(c)

Figure 21 (a) Upstream signal, (b) Downstream signal, and (c) Cross correlation function of rectangular- shaped electrode in distance=15 cm, sampling frequency= 1 KHz

Table 4 Experimental results of rectangular- shaped electrode in sampling frequency= 1 KHz

Distance (cm)	Correlogram peak(v)	Time lag (ms)	Velocity (m/s)
5	0.0184	16	3.125
10	-0.0016	31	3.2258
15	-0.0019	45	3.3333
20	-0.0020	52	3.8461

Velocity measurement are examined in different distance by experimental tests and the results show velocity is roughly constant while distance is changed but the time lag has directly changed by changing the distance.

4.0 RESULTS AND DISCUSSON

The validity of the proposed model is confirmed by comparison of experimental data with the analytical calculations. Application of the approach defined on a set of experimental data can compute the parameters based on a certain electrode and sensor system that this fact increase the practical importance of equation, which is used to forecast and plan goals.

Good agreement between mathematical and experimental results, assured applying of the model for measuring the velocity of particles in pipeline As be mentioned, characteristics of different types of electrodes[15-16] were analyzed experimentally and mathematically in this paper. The results by mathematical equation verify that shapes of electrodes do not influence on output signals. Figures (5), (8), (11), and (14) show the similarity between output signals of these electrodes. In addition, experimental and a mathematical output signals are compared with each other and verified this model. Distance acts as significant role on velocity. On the one hand, 5 cm distance is good because it causes high cross correlation coefficient. On the other hand, it leads to interaction of electrical field between electrodes. Therefore, a suitable distance should be considered. When distance between electrodes is about 15 cm, the output signal is better than other distances and the cross correlation coefficient also is as well as the output signal.

5.0 CONCLUSION

This paper discussed not only about the effects of different shapes of electrodes, including circular, quarter-ring, rectangular and pin electrode but also about the effects of different distance between electrodes on output signals. It is evident that output signals of different electrodes are similar to each other but distance influence on velocity and lead to lower cross correlation coefficient if the distance between electrodes is high. To calculate the induced charge, a point charge is considered in pipeline and is modeled by mathematical equations. A laboratory setup is constructed to measure the velocity. To achieve this target, cross correlation method is applied. At first, the upstream and downstream signals are captured by experimental tests in laboratory, which they show the output voltage from the sensors, then they are analyzed by Matlab code and give cross correlation curve. The peak of cross correlation curve determines time delay that particles move between electrodes. Finally, velocity can be measured by the distance between electrodes and given time delay. Tables of experimental tests show when the distance between electrodes is increasing, the time lag is also increasing but velocity is constant between 3 m/s–4 m/s. The maximum flow velocity of particles in this research is about 4.4272 m/s, which is calculated by this equation $v = \sqrt{2gh}$, where g is the g
According to experimental results, when the distance equals to 15 cm, cross correlation function of all of electrodes are very good; in addition there are not any interaction of electrical field and noise on the signals. The sensitivity is not important factor in this research and output voltage only has significant role.

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