Bukti Korespondensi Artikel Jurnal

Nama: Asep Yoyo Wardaya
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No	Tanggal	Aktivitas Korespondensi	Halaman
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3.	23 Nov 2017	Proses submission jurnal INJP	2
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10.	14 Jan 2019	Makalah Revisi	23-35
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12.	20 April 2019	Jurnal Publish	37-selesai

Proses submission jurnal INJP, 16 Nov 2017,

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4. Please provide only reference numbers serially in 3rd bracket inside Text [NOT like (Wardaya and Nur, 2015),]and the full reference may be mentioned in the REFERENCE SECTION in correct format of Indian Journal of Physics.

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b) NO TITLE OF THE PAPER IN THE REFERENCE.
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d) NO FULL STOPS after authors initial name followed by surname in reference section.
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Correct sequence: Volume (in bold font) Initial page number (Year)

For example: [1] X Q wang, D Xu, M K Lu, D R Yuan and S X Xu Materials research bulletin (in italic font) 36 (in bold and no issue number) 879 (only first page no.) (2001)

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--

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Coordinator
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Action	Manuscript Number	Title	Date Submission Began	Status Date	Current Status
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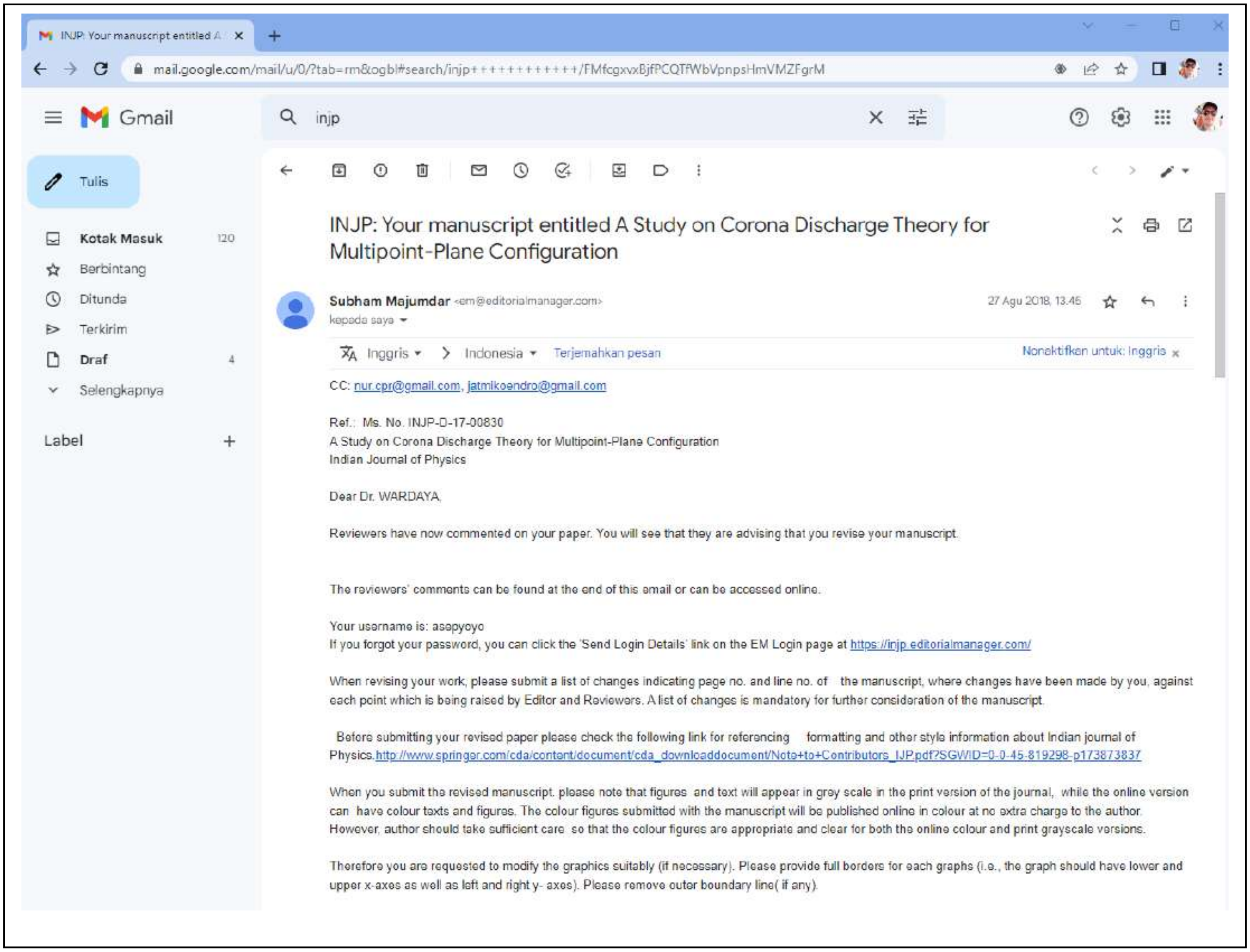

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A Study on Corona Discharge Theory for Multipoint-Plane Configuration
Indian Journal of Physics

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Reviewers have now commented on your paper. You will see that they are advising that you revise your manuscript.

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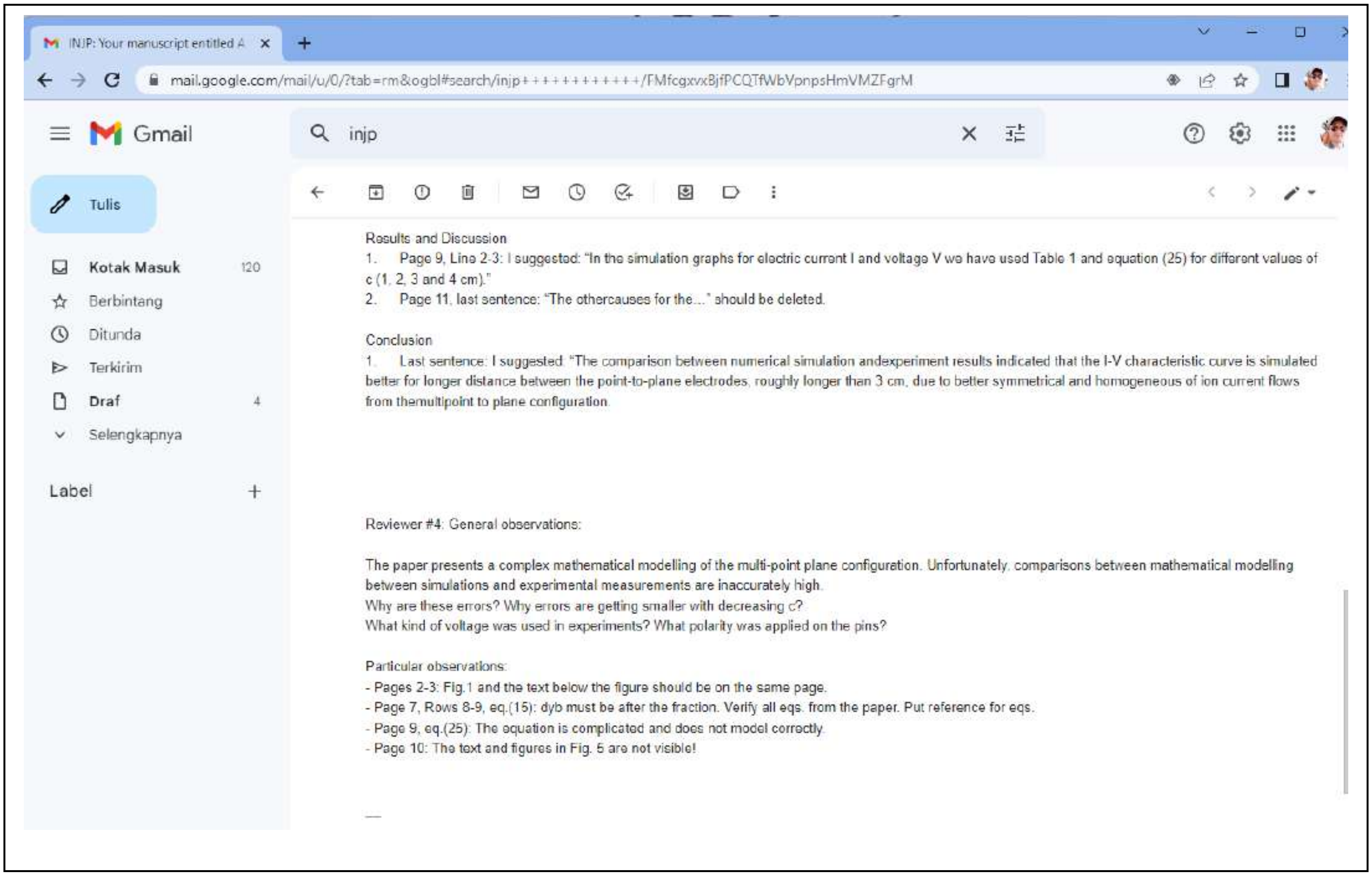
Yours sincerely

Subham Majumdar
Editor-in-Chief
Indian Journal of Physics

Reviewers' comments:

Reviewer #2: Comments:
Abstract
1. Line 16-18: I suggested: This paper presents numerical calculation of current-voltage (I-V) characteristics which were produced by corona discharges plasma generator for multipoint-plane configuration in air, its comparison with experimental results.
2. Line 19-20: I suggested: "…configuration is 8 × 4 = 32 pieces with the distance between the point-to-plane electrodes (denoted as c) being the variable."
3. Line 22-24: I suggested: "…calculation results matches with that of experimental results for cases of large distance c (c = 3 and 4 cm) and it shows large deviation for …"
4. Line 22-24: I suggested: "…between experiment and numerical results is due to symmetrical spreading of ion current from the point-to-plane electrodes, which is more pronounced for largerc.
Introduction
1. Page 1; Line 55 and on: I suggested to use the principle or the author's names of references, instead of the title of the cited papers. For example, "… among which are electrical potential distribution of pin-multi ringconcentric electrodes [7], electro hydrodynamic and wind ions directionproduced by plasma discharge [8], … etc".
2. Page 2, Line 24: I suggested: "This research is considered as an extension of the work reported byJaworek and Krupa [6]…"
3. Page 2, Line 35: I suggested: "In this study, we use a model of multipoint-plane configuration which consists…"
4. Page 2, Line 46: I suggested: "… position, we take it as if the upper part…"
5. Page 3, Line 40-42: I suggested: "… can be expressed similarly to equation [1] …"
6. Page 6, Line 44: I suggested: "We can consider that there is an arrangement of m×nnumber of…"
7. Page 7, Line 1-6: "Actually, the ions flow continuously toward area xy= (A-1)(B-1)…." This sentence is not clear, it needs rewording or rephrase.
8. Page 7, Line 20: I suggested: "and this generates electric field as given by"
9. Page 7, Line 30: I suggested: "We note that not all point at positions…"
10. Page 8, Line 6: I suggested: "In order to verify the numerical simulations, we have carried out an experiment to figure out…."
11. Page 8, last sentence: I suggested: "…q is the moving charge on its flux lines with by using eq. (20),…."This sentence is not clear, it needs rewording or rephrase.
12. Page 9, Line 33: I suggested: "When the results from the work of Coelho andDebeau [1]…"



Results and Discussion

1. Page 9, Line 2-3: I suggested: "In the simulation graphs for electric current I and voltage V we have used Table 1 and equation (25) for different values of c (1, 2, 3 and 4 cm)."
2. Page 11, last sentence: "The othercauses for the..." should be deleted.

Conclusion

1. Last sentence: I suggested: "The comparison between numerical simulation andexperiment results indicated that the I-V characteristic curve is simulated better for longer distance between the point-to-plane electrodes, roughly longer than 3 cm, due to better symmetrical and homogeneous of ion current flows from themultipoint to plane configuration.

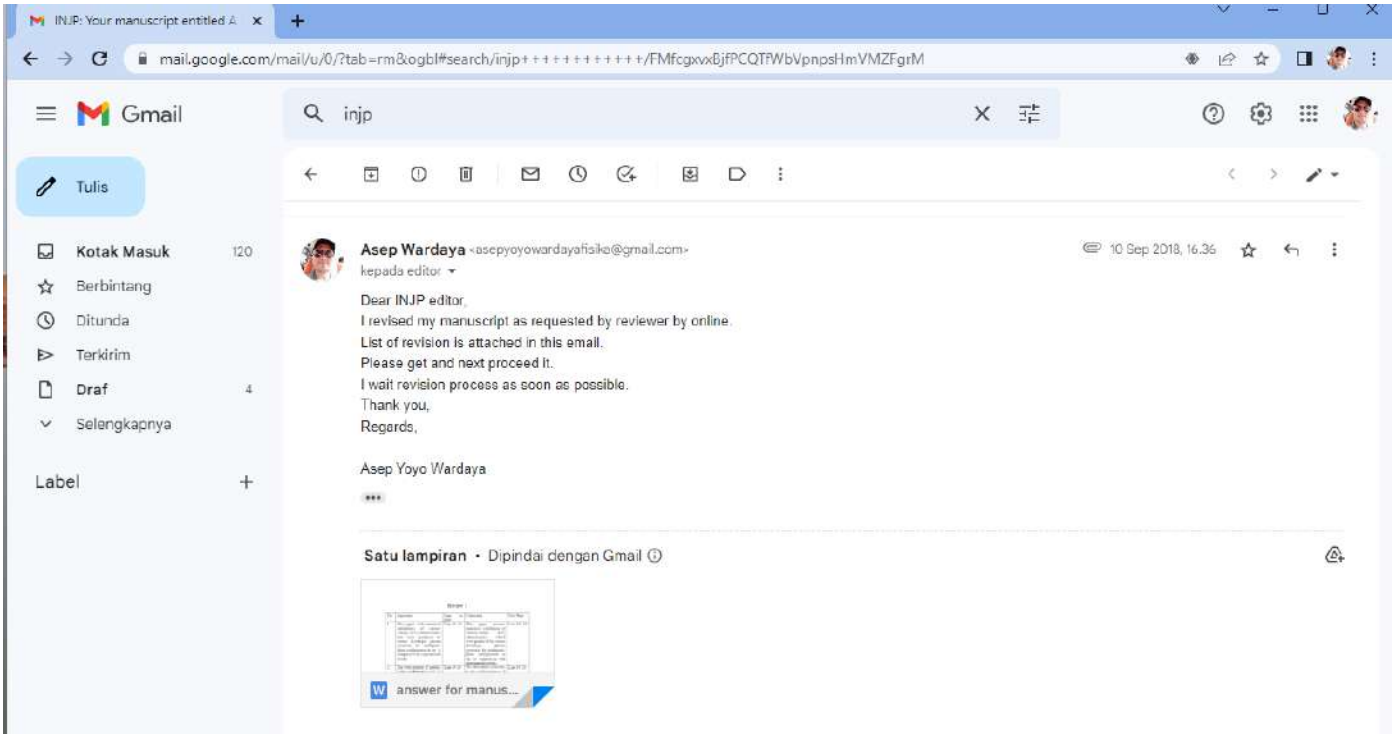
Reviewer #4: General observations:

The paper presents a complex mathematical modelling of the multi-point plane configuration. Unfortunately, comparisons between mathematical modelling between simulations and experimental measurements are inaccurately high.
Why are these errors? Why errors are getting smaller with decreasing c?
What kind of voltage was used in experiments? What polarity was applied on the pins?

Particular observations:
- Pages 2-3: Fig.1 and the text below the figure should be on the same page.
- Page 7, Rows 8-9, eq.(15): dyb must be after the fraction. Verify all eqs. from the paper. Put reference for eqs.
- Page 9, eq.(25): The equation is complicated and does not model correctly.
- Page 10: The text and figures in Fig. 5 are not visible!

—

Proses submission jurnal INJP, 10 September 2018



Answer for manuscript revision

Review 1

No	Sugestion	Line or page	Correction	New Page
1.	This paper with numerical calculations of current-voltage (I-V) characteristics that were produced by corona discharges plasma generator for multipoint-plane configuration in air, is compared with experimental results.	Line 16 - 18	This paper presents numerical calculation of current-voltage (I-V) characteristics which were produced by corona discharges plasma generator for multipoint-plane configuration in air, its comparison with experimental results.	Line 16 - 19
2.	The total number of needles in this configuration is 8 × 4 = 32 pieces and there is variation of *c*, which is the distance between the point-to-plane electrodes	Line 19-20	The total number of needles in this configuration is 8 × 4 = 32 pieces with the distance between the point-to-plane electrodes (denoted as c) being the variable.	Line 19 - 23
3.	The *I-V* characteristic curve of numerical calculation results matches that of experimental results for cases of large distance *c* (*c* = 3 and 4 cm) and does not match for cases of small distance *c* (*c* = 1 and 2 cm).	Line 22-24:	The *I-V* characteristic curve of numerical calculation results matches with that of experimental results for cases of large distance c (c = 3 and 4 cm) and it shows large deviation for cases of small distance *c* (*c* = 1 and 2 cm).	Line 23 - 26
4.	Differences in I-V	Line 25-	Differences in I-V characteristic curve	Line 26 -

	characteristic curve between experiment and numerical results for cases of small c is caused by more symmetrical spreading of ion current from the point-to-plane electrodes for large *c* cases than for small c cases.	27:	between experiment and numerical results is due to symmetrical spreading of ion current from the point-to-plane electrodes, which is more pronounced for larger c.	30
Introduction				
1.	Some other research calculate values related to corona discharges, among which are *Electrical Potential Distribution from EHD Flow Zone Using Pin-Multi Ring Concentric Electrodes* [7], *Study of Electro hydrodynamic and Wind Ions Direction. Produced by Positive Corona Plasma Discharge* [8], *Calculation of Ionic Wind Generation Using Voltage and Electric Current Characteristics from DC Needle-to-Cylinder Electrode Model* [9], *Calculation of Ionic Wind Generation Using Geometrical*	Page 1; Line 55 and on	Some other research calculate values related to corona discharges, among which are electrical potential distribution of pin-multi ring concentric electrodes [7], electro hydrodynamic and wind ions direction produced by plasma discharge [8], *Ionic Wind Generation of Needle-to-Cylinder Electrode Model* [9], *Ionic Wind Generation of Multi Electrode Model* [10], *Electro hydrodynamic Force by A Corona Discharge* [11]. There are also research that discuss direct application of corona discharge electrode configuration, among those are *Cold Large-Diameter Plasma Jet of A Triple Electrode Model* [12], *Electric Potential Distribution of Various Electrode models* [13], and *Laser-Induced Streamer Corona Discharge of A Needle-to-Plate Electrode Model* [14].	Page 1; line 53 – Page 2; line 11.

	Analysis of Multi Electrode Model Miniature Scaling (Gate Electrode and Collector Electrode) [10], *Calculation of Electro hydrodynamic Force From Low Speed Electric Propulsion System Generated by A Corona Discharge between A Wire Active Electrode and Several Cylinder Electrodes* [11]. There are also research that discuss direct application of corona discharge electrode configuration, among those are *Cold Large-Diameter Plasma Jet Near Atmospheric Pressure Produced by A Triple Electrode Discharge Configuration* [12], *Determining Electric Potential Distribution on Isolator Surfaces Exposed to Corona Discharges from Various Electrode Configurations* [13], and *Characteristics of*			

	Laser-Induced Streamer Corona Discharge in A Needle-to-Plate Electrode System [14].			
2	This research is a continuation from the work of Jaworek and Krupa [6]	Page 2, Line 24	"This research is considered as an extension of the work reported by Jaworek and Krupa [6]…"	Page 2; line 13 – 14.
3	This research uses a model of multipoint-plane configuration that consists…	Page 2, Line 35:	"In this study, we use a model of multipoint-plane configuration which consists…"	Page 2; line 25.
4	position, take it as if the upper part …	Page 3, Line 46:	"… position, we take it as if the upper part…"	Page 3; line 42.
5	can be stated as equation as [1]	Page 4, Line 40-42:	"… can be expressed similarly to equation [1] …"	Page 4; line 40 - 42.
6	Say there is an arrangement of $m \times n$ number of	Page 6, Line 44:	"We can consider that there is an arrangement of m×n number of…"	Page 6; line 40.
7.	"…,B-1, in discrete. Actually, the ions flow continuously toward area xy=(A-1)(B-1)…." This sentence is not clear, it needs rewording or rephrase.	Page 7, Line 1-6:	…B-1, where A and B are the number of maximum points on plate surface which exposed by ion current at coordinates of x and y respectively, in discrete numbers. These ion current will flow from needle tip to the plate surface with the maximum plate area is $xy = (A-1)(B-1)a^2$. Because ion current flux has the properties of symmetrical, homogeneous and continuous when arrive on plane configuration then discrete characteristic (summation form) in eq. (14) is become the continuous characteristic (integration form) of the electric field quantity that can be solved at eq (15) below.	Page 6; line 55 – Page 7; line 7.
8	and this generates electric field	Page 7, Line 20:	"and this generates electric field as given by"	Page 7; line 22.
9	Not all points at position	Page 7, Line 30:	"We note that not all point at positions…"	Page 7; line 32.
10	An experiment to figure out	Page 8, Line 6:	"In order to verify the numerical simulations, we have carried out an	Page 8; line 5 –

			experiment to figure out….”	7.
11	"…q is the moving charge on its flux lines with by using eq. (20),….”This sentence is not clear, it needs rewording or rephrase.	Page 8, last sentence	"…q is the charge of electric flux lines that is coming out of the multipoint to the plane configurations as defined in eq. (20),….”	Page 9; line 1 – 2.
12	When Coelho dan Debeau [1]	Page 9, Line 33:	"When the results from the work of Coelho and Debeau [1]…”	Page 9; line 38.
		Results and Discussion		
1	Using Table 1 and equation (25) for varied c of 1, 2, 3 and 4 cm results in simulation graphs for various electric current *I* and voltage *V*.	Page 10, Line 2-3:	"In the simulation graphs for electric current I and voltage V we have used Table 1 and equation (25) for different values of c (1, 2, 3 and 4 cm).”	Page 10; line 11 – 13.
2	The other causes for the slight mismatch between simulation and experiment results are errors in terms of measurement, electric device, and asymmetry	Page 11, last sentence:	deleted.	-
		Conclusion		
1	The comparison between modeling and experiment results stated more and more distance *c* then the *I-V* characteristic curve will nearest similar because more symmetrical and homogeneous of ion current flows from the multipoint to plane configuration.	Last sentence	The comparison between numerical simulation and experiment results indicated that the I-V characteristic curve is simulated better for longer distance between the point-to-plane electrodes, roughly longer than 3 cm, due to better symmetrical and homogeneous of ion current flows from the multipoint to plane configuration.	Last sentence

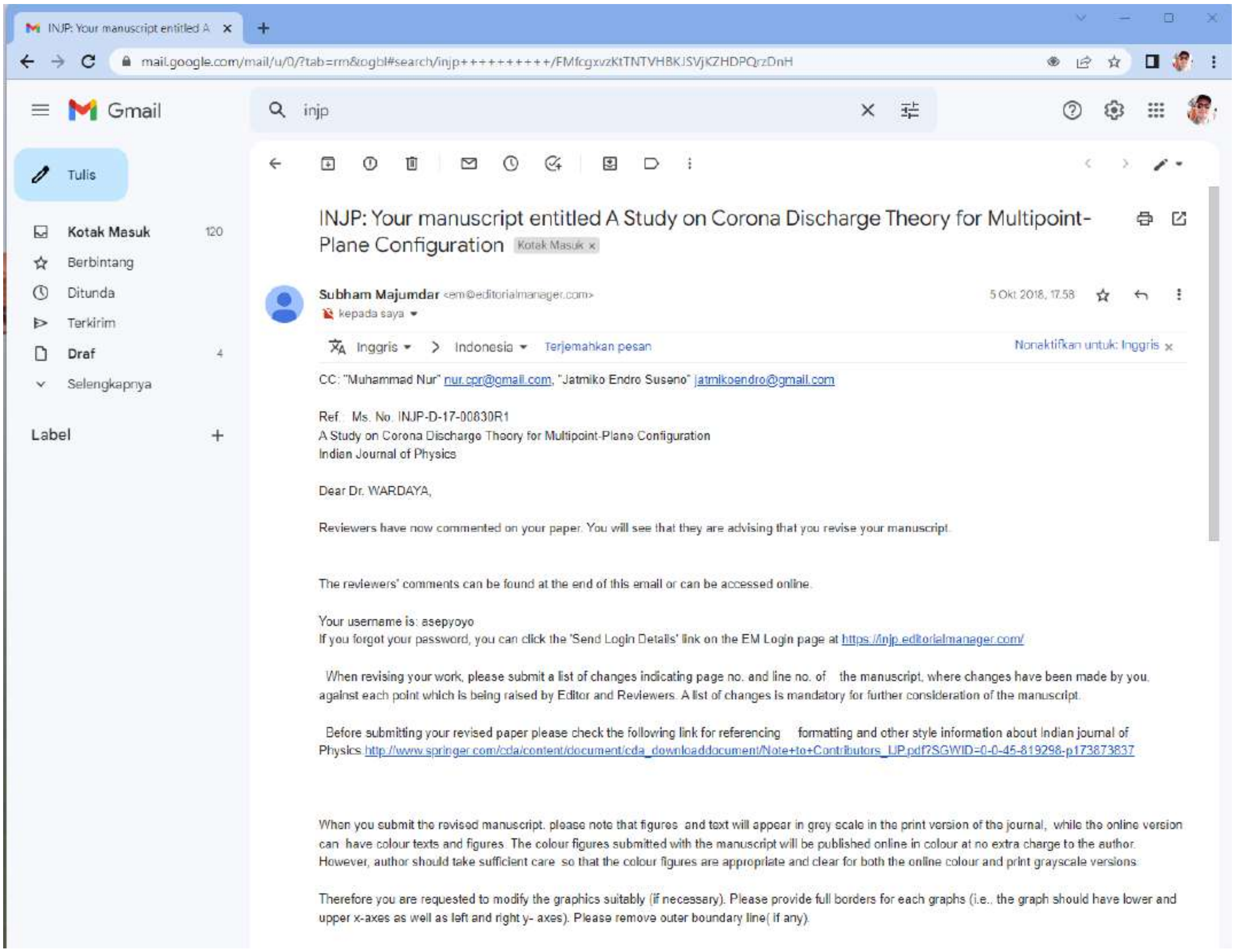
Review 2

No	Sugestion	Line or page	Correction	New Chapter, line and Page
1.	The paper presents a complex mathematical modelling of the multi-point plane configuration. Unfortunately, comparisons between mathematical modelling between simulations and experimental measurements are inaccurately high. Why are these errors? Why errors are getting smaller with decreasing c?	-	These statements can be explained as follows, Equation (14) shows the 3-dimensional vector of the ion current flow model which flows from needle tip to the bottom plate with the parabolic shape as shown in Figure 3. To simplify equation (14), we assume that the ion current flows symmetrically so that the flowing 3-dimensional vector will be changed become one direction of the upright axis (Z axis) because the ion current direction at the XY plane will be symmetrical circle therefore it will be eliminate each others. Another assumption is that the ion current in the direction of the Z axis will be homogenous distributed and close to continuous flowing, so that the vector and discrete (summation) characteristics in equation (14) changed be the continuous (integration) and scalar characteristics (only in the direction of the axis Z) in equation (15), where equation (15) is	Results and Discussion, last sentence.

			part of equation (25). Therefore, the conditions of homogenous continuity and symmetry will be better for the distance of among the multipoint to the bottom plate surface is increaser, so that the mathematical simulation will be match the results of the experiment at the greater value of c.	
2.	What kind of voltage was used in experiments? What polarity was applied on the pins?	-	The Experiment of Corona discharge for multipoint- plane configuration uses DC voltage, with a positive polarity position at the point position and negative polarity at the plane position	Page 3, line 3 – 7.
3	Fig.1 and the text below the figure should be on the same page.	Pages 2-3.	Fig.1 and the text have been done on the same page.	Page 2, line 31 – 59.
4	eq.(15): dyb must be after the fraction. Verify all eqs. from the paper. Put reference for eqs.	Page 7, Rows 8 - 9.	A full explanation of the appearance of equation (15) is written in the results and discussion section. There are : "To simplify equation (14), we assume that the ion current flows symmetrically so that the flowing 3-dimensional vector will be changed become one direction of the upright axis (Z axis) because the ion current direction at the XY plane will be symmetrical circle therefore it will be eliminate each others. Another assumption is that the ion current in the	Results and Discussion, Page 11, line 35 – 48.

			direction of the Z axis will be homogenous distributed and close to continuous flowing, so that the vector and discrete (summation) characteristics in equation (14) changed be the continuous (integration) and scalar characteristics (only in the direction of the axis Z) in equation (15)". We have put references in equations of (1) - (7). The next equations do not have references because we calculate ourselves based on the condition of laboratory equipment and experimental models.	 Page 3, line 17 – Page 5, line 7.
5	eq.(25): The equation is complicated and does not model correctly.	Page 9	Actually, model from the equation. (25) have described the real experiment result such as an ion flow calculation from multi-point to plane configurations which includes the calculation of the number of needles, parabolic trajectory of the electrical flux and the areas of the plane configuration that is exposed by electrical flux. So the equation can't be simplified and have explained in the chapter of results and discussion.	-
6.	The text and figures in Fig. 5 are not visible!	Page 10.	The text and figures in Fig. 5 have been corrected.	Page 10.

Proses submission jurnal INJP, 5 Oktober 2018



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Indian Journal of Physics

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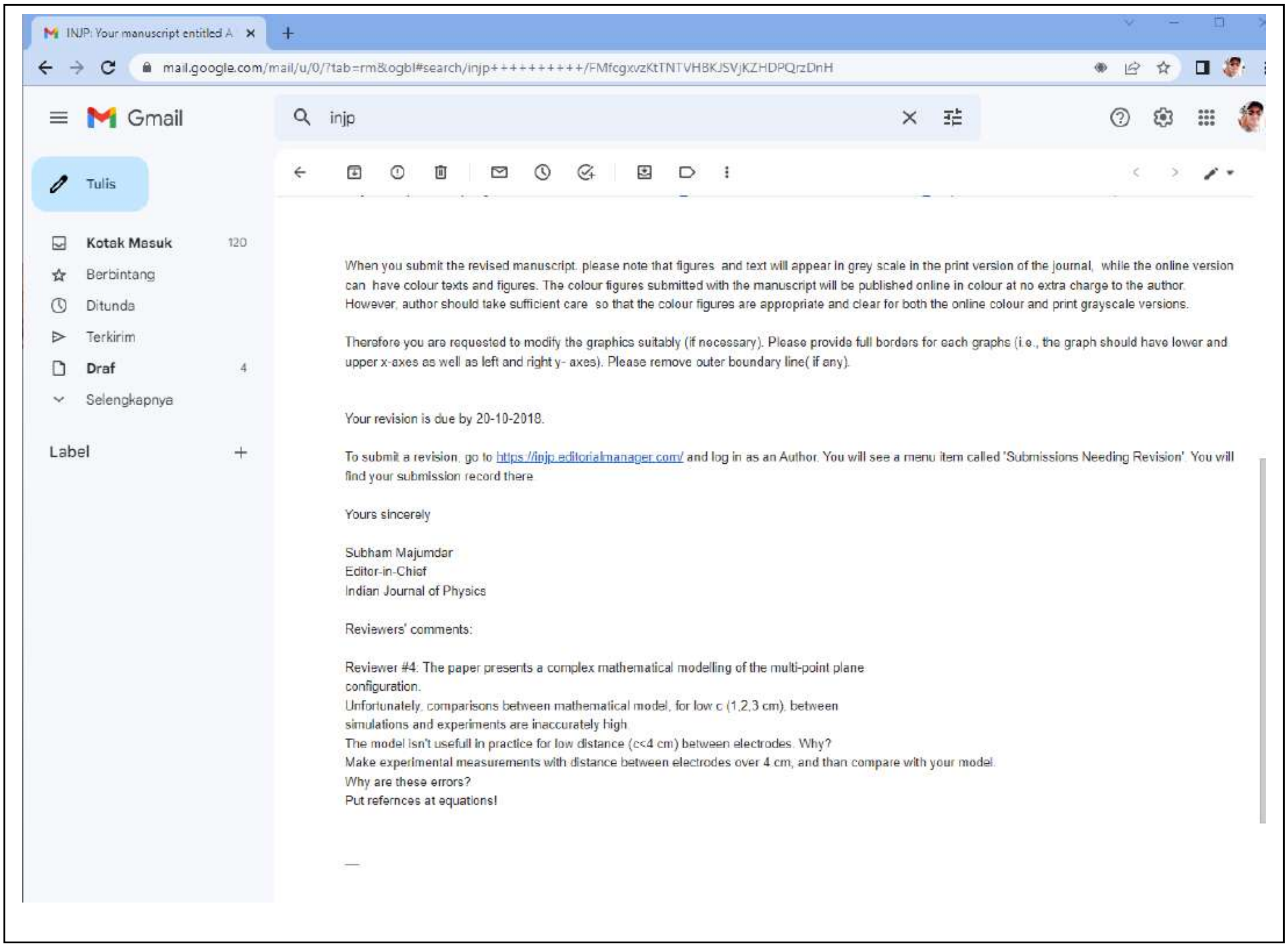

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Yours sincerely

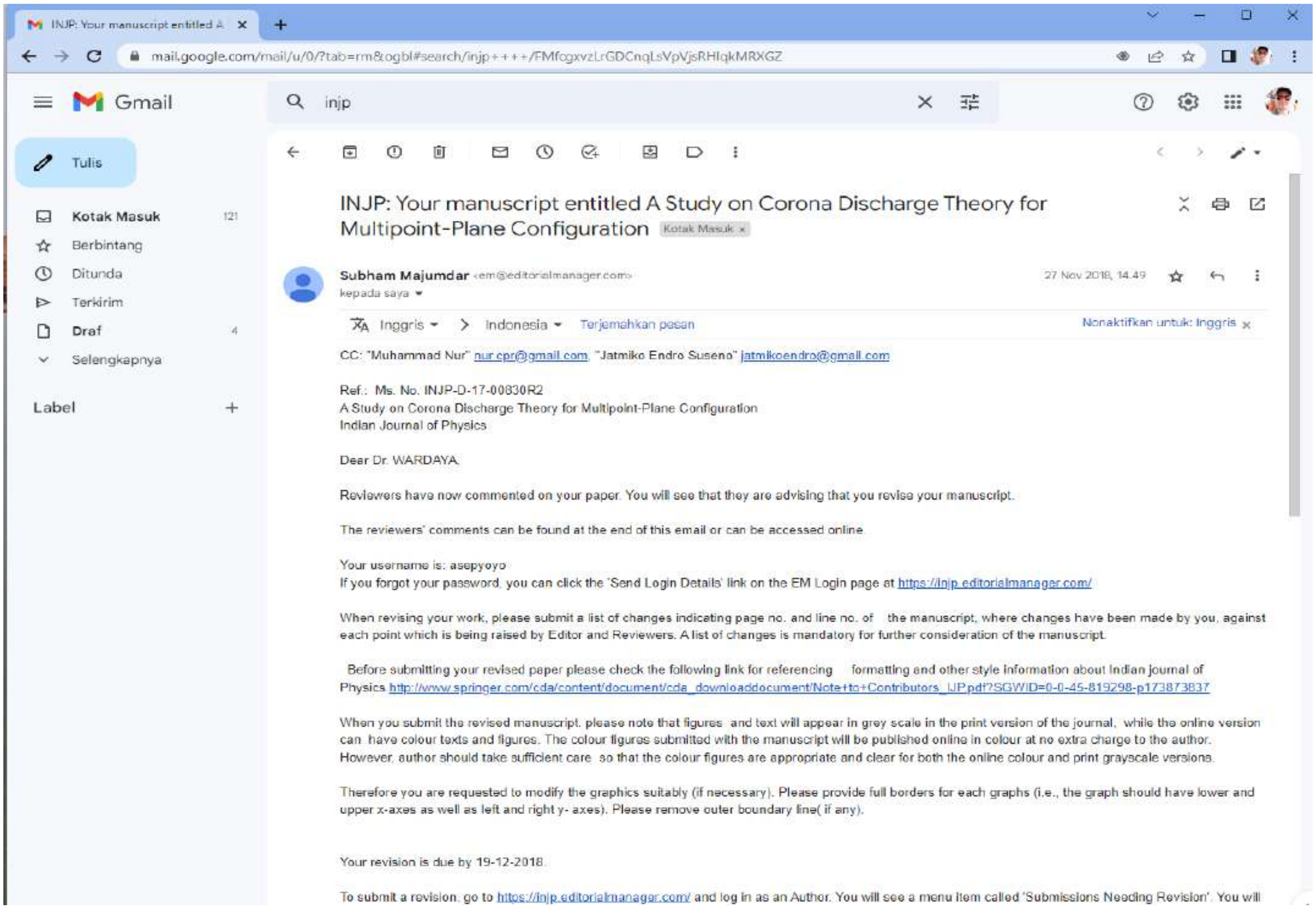
Subham Majumdar
Editor-in-Chief
Indian Journal of Physics

Reviewers' comments:

Reviewer #4: The paper presents a complex mathematical modelling of the multi-point plane configuration.
Unfortunately, comparisons between mathematical model, for low c (1,2,3 cm), between simulations and experiments are inaccurately high.
The model isn't usefull in practice for low distance (c<4 cm) between electrodes. Why?
Make experimental measurements with distance between electrodes over 4 cm, and than compare with your model.
Why are these errors?
Put refernces at equations!

—

Proses submission jurnal INJP, 27 November 2018



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A Study on Corona Discharge Theory for Multipoint-Plane Configuration
Indian Journal of Physics

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Reviewers have now commented on your paper. You will see that they are advising that you revise your manuscript.

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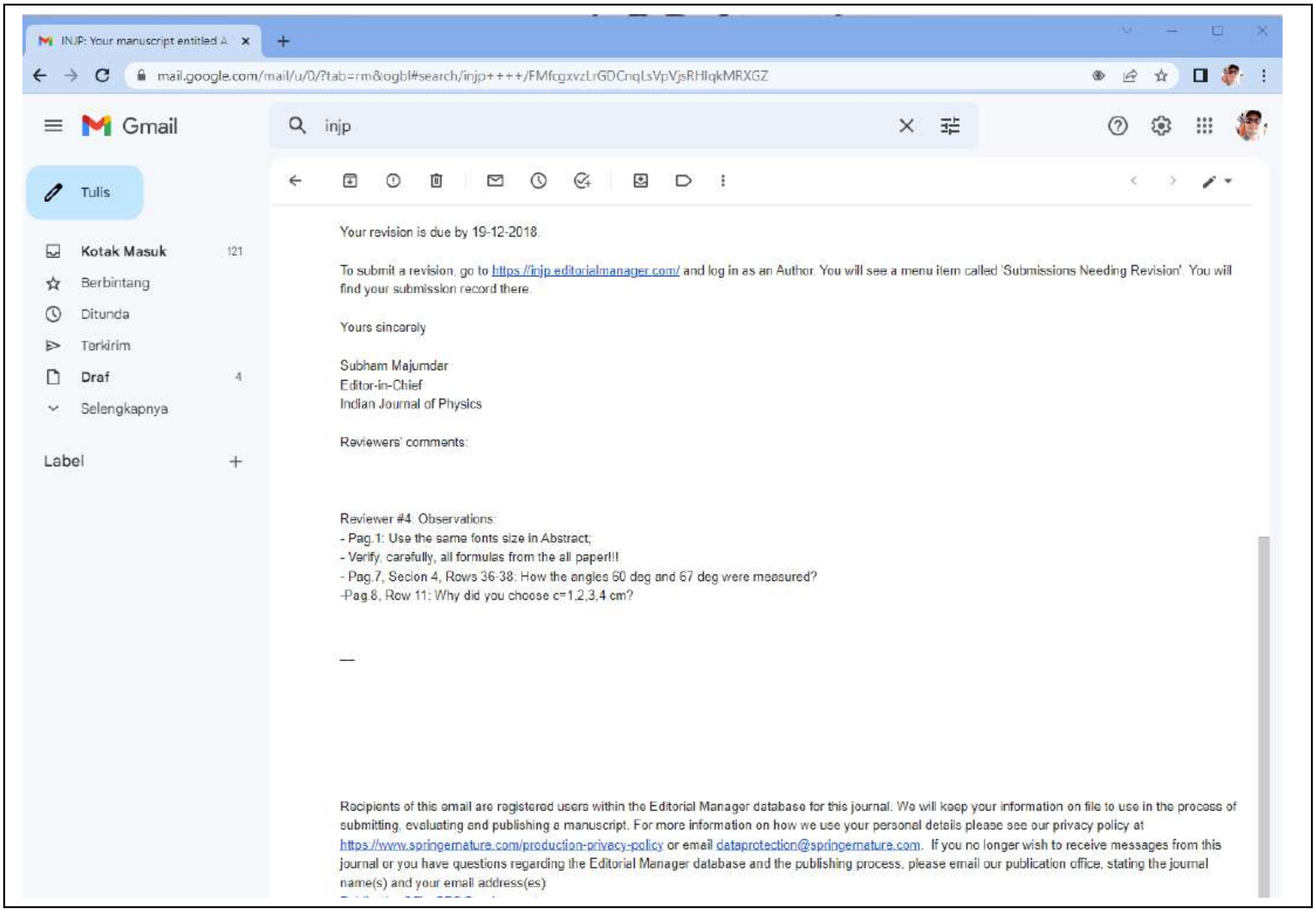

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Reviewer #4: Observations:
- Pag.1: Use the same fonts size in Abstract;
- Verify, carefully, all formulas from the all paper!!!
- Pag.7, Secion 4, Rows 36-38: How the angles 60 deg and 67 deg were measured?
-Pag.8, Row 11: Why did you choose c=1,2,3,4 cm?

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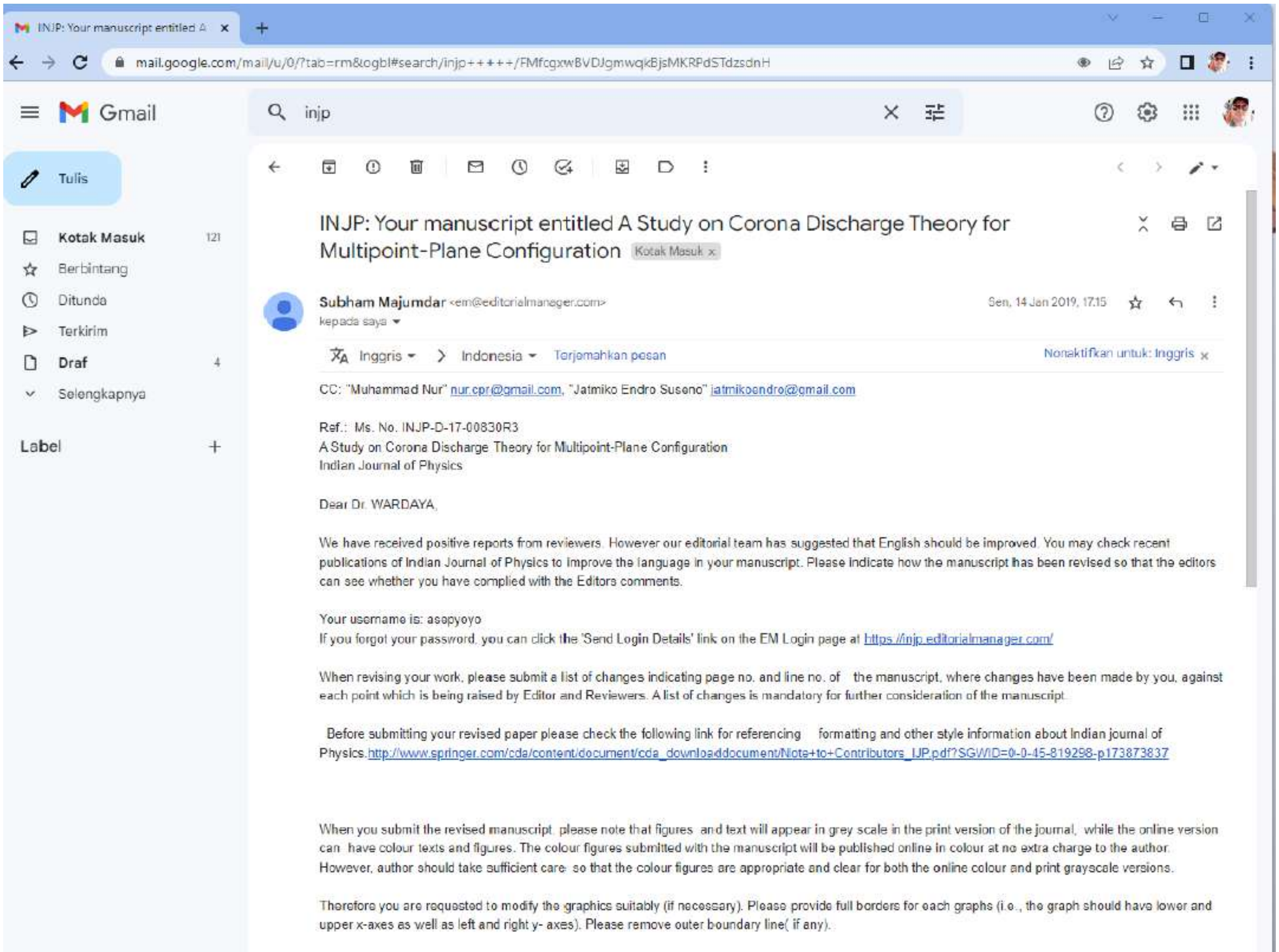

INJP: Your manuscript entitled A Study on Corona Discharge Theory for Multipoint-Plane Configuration

Subham Majumdar <em@editorialmanager.com> Sen, 14 Jan 2019, 17.15

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CC: "Muhammad Nur" nur.cpr@gmail.com, "Jatmiko Endro Suseno" jatmikoendro@gmail.com

Ref.: Ms. No. INJP-D-17-00830R3
A Study on Corona Discharge Theory for Multipoint-Plane Configuration
Indian Journal of Physics

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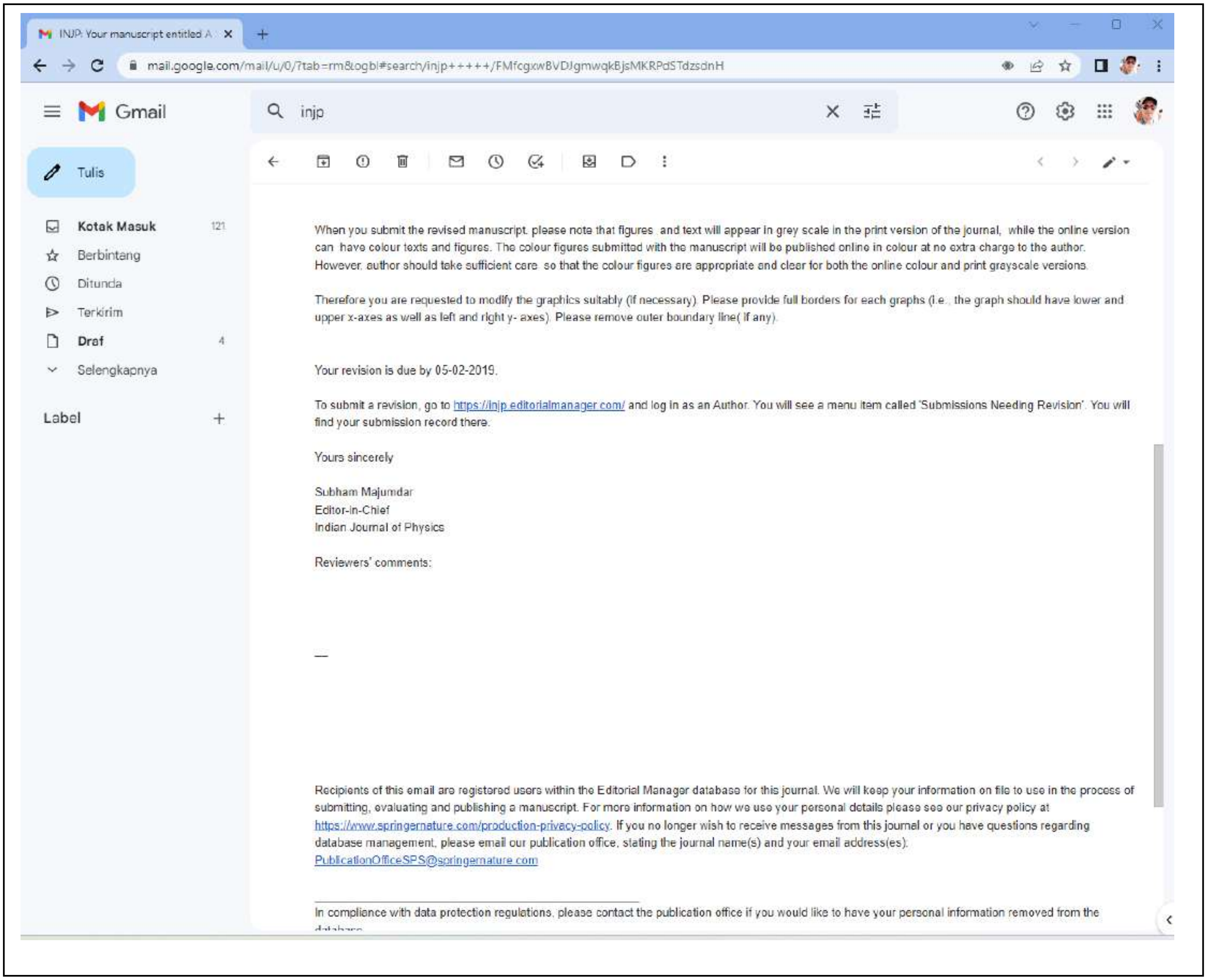

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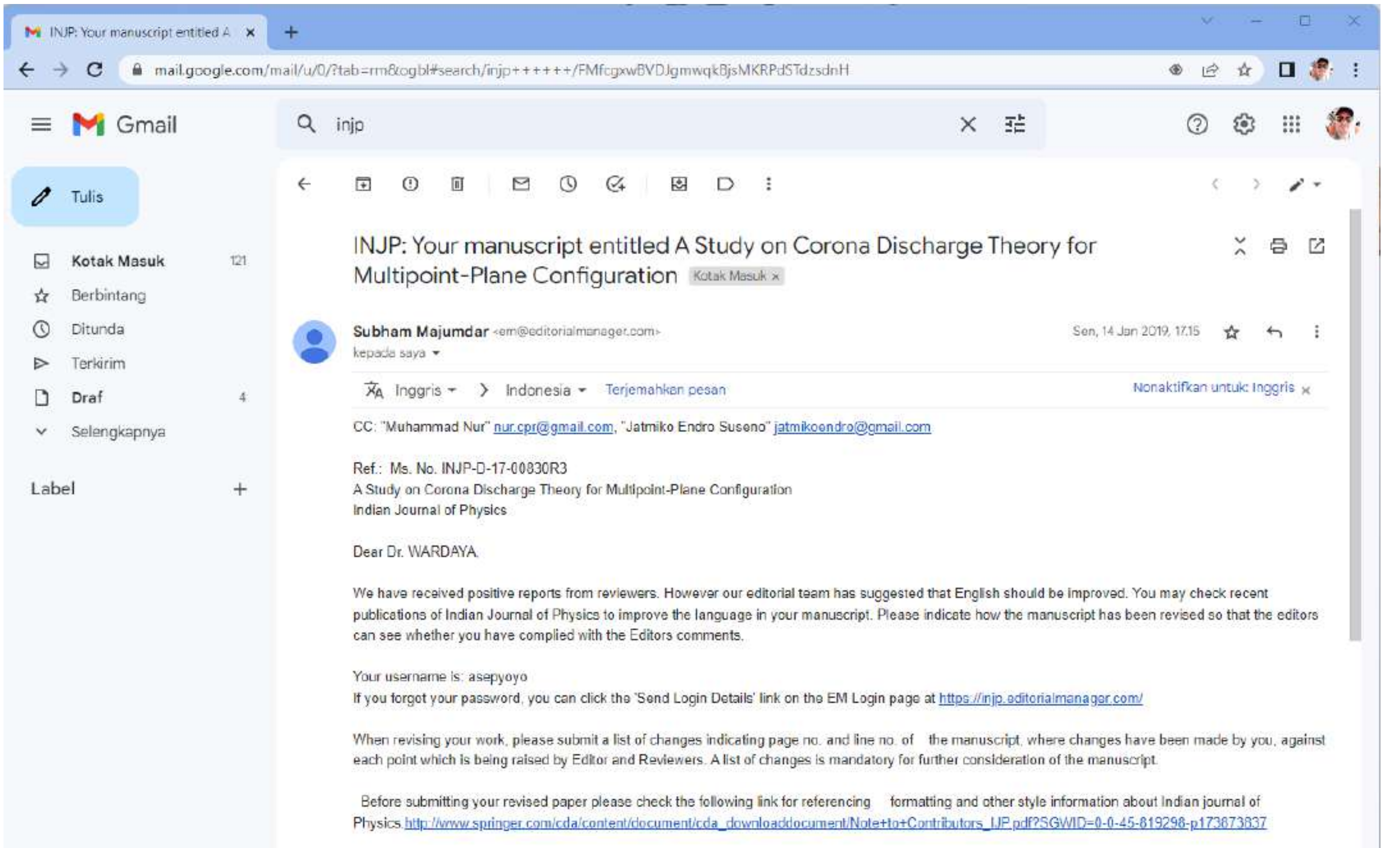

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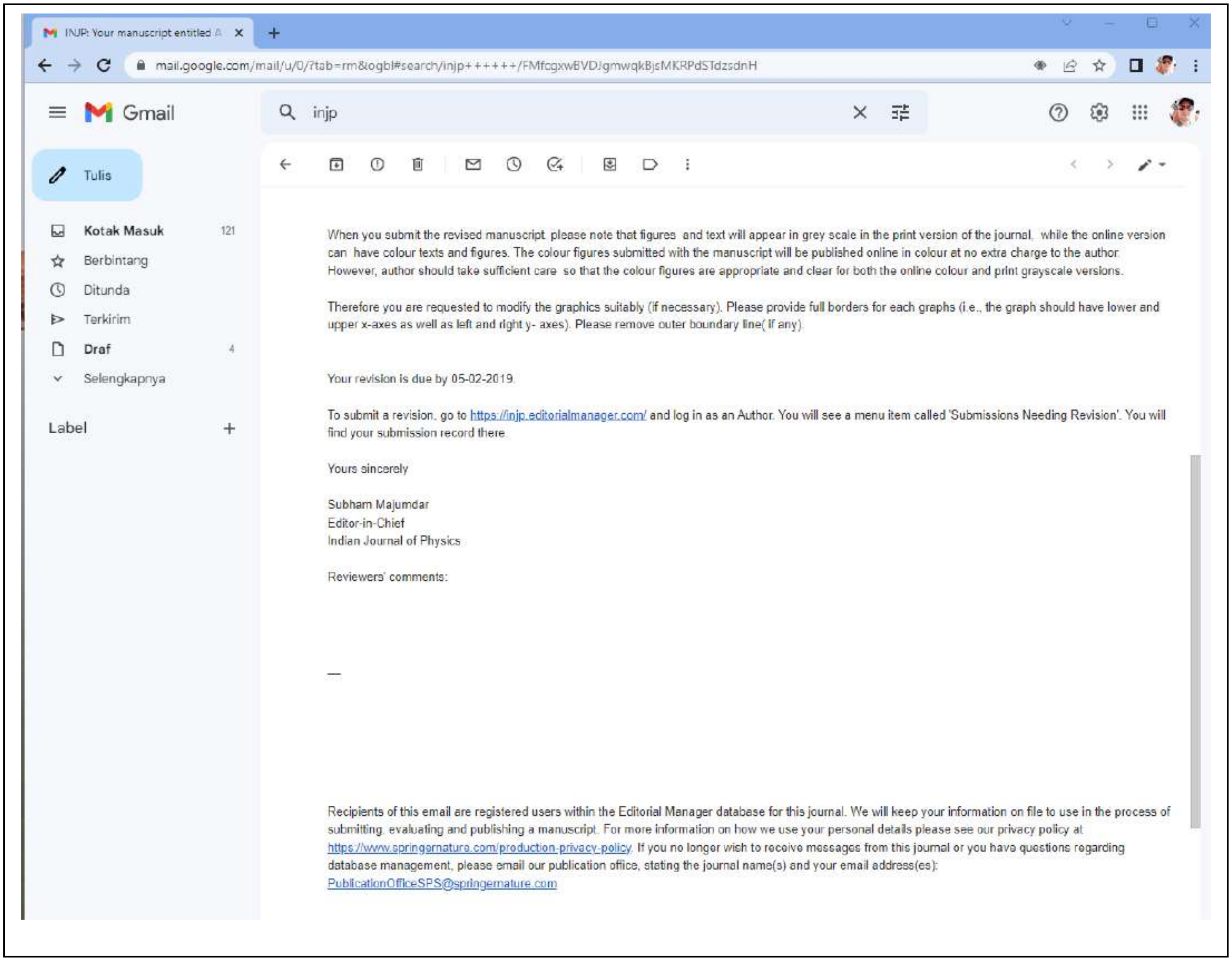

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Makalah Revisi

A Study of the Corona Discharge Theory for Multipoint-Plane Configurations

***A Y Wardaya*[1,2]*, *M Nur*[1], *J E Suseno*[1]**

[1]*Department of Physics, Faculty of Science and Mathematics, Diponegoro University, Semarang Indonesia*

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Abstract: This paper presents the numerical calculation of current-voltage (*I-V*) characteristics that were produced by a corona discharges plasma generator for a multipoint-plane configuration in air and; its comparison with the experimental results. The total number of needles in this configuration is 8 × 4 = 32 with the distance between the point-to-plane electrodes (denoted as *c*) as the variable. The *I-V* characteristic curve of the numerical calculation results matches that of the experimental results for cases with a large distance *c* (*c* = 3 and 4 cm), and it shows a large deviation for cases with a small distance *c* (*c* = 1 and 2 cm). Differences in the *I-V* characteristic curve between the experimental and numerical results are due to the symmetrical spread of the ion current from the point-to-plane electrodes, which is more pronounced for larger values of *c*.

Keywords: Plasma generator, multipoint-plane configuration, electric field, electric current, *I-V* characteristics.

PACS Nos.: 02.30.−f; 02.30.Em; 02.30.Ik; 02.30.Mv; 02.70.−c

1. Introduction

The corona discharge technique has been widely used for various research studies. Some of the papers on various electrode model configurations of corona discharges that try to obtain potential, voltage, or electric current characteristic values include the tip-plane configuration [1], thin bar-needle configuration [2], cylinder-wire-plate configuration [3], sub-millimeter electrode gap configuration [4], point-to-ring configuration [5], and multipoint-plane configuration [6]. However, this paper discusses the current-voltage characteristics from the experimental results.

Some other research studies have calculated values related to corona discharges, among which are electrical potential distribution of pin-multi-ring concentric electrodes [7], electro-hydrodynamic and wind-ion direction produced

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by plasma discharge [8], ionic wind generation of needle-to-cylinder electrode model [9], ionic wind generation of multi electrode model [10], electro hydrodynamic force by a corona discharge [11].

There are also research studies that discuss the direct application of the corona discharge electrode configuration; cold large-diameter plasma jet of a triple electrode model [12], electric potential distribution of various electrode models [13], and laser-induced streamer corona discharge of a needle-to-plate electrode model [14].

This research is considered an extension of the work reported by Jaworek and Krupa [6] for the case of comparing the numerical calculation and experimental results of voltage and electric current characteristics generated by a corona discharge from plasma electrodes using a multipoint configuration. According to Sigmond [15], a large electric field generation along with a saturated current in the form of a corona discharge that, in turn, produces corona plasma is due to the sharp end of one of the electrodes; and the asymmetrical shape of both electrodes.

In this study, we use a model of a multipoint-plane configuration that consists of two perpendicular plates on one of which $m \times n$ number of needles is attached, as depicted in Fig. 1.

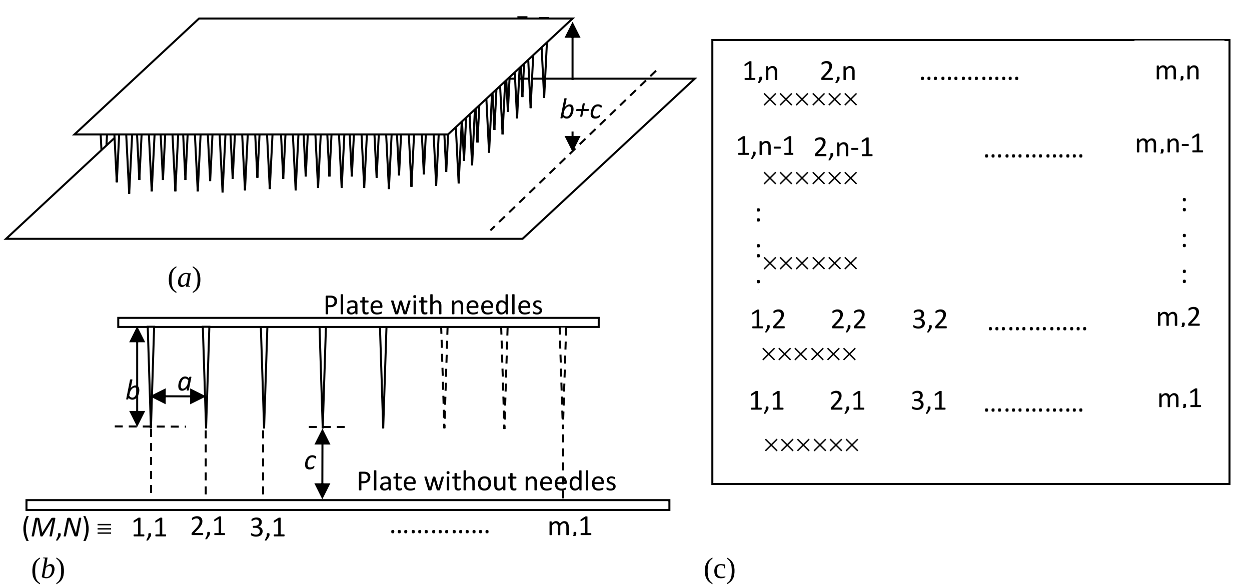


Figure 1. Model of the multipoint-plane configuration consisting of two parallel plates on one of which $m\times n$ needles are attached. The inter-needle distance is *a*, needle length is *b*, and distance between the point-to-plane electrodes is *c*. a). 3D representation of the electrode model. b). Side view of the electrode model. c). Top view of the location of $m\times n$ needles (marked ×).

As seen in Fig. 1, the needle length is *b*, inter-needle space is *a*, and distance between the point-to-plane electrodes is *c*. Hence, the distance between the two thin plates is $b + c$.The experiment of the corona discharge for the multipoint-plane configuration uses DC voltage; with a positive polarity position at the point position and negative polarity at the plane position.

2. Electric Field Intensity

The electric field generated by the corona discharge from the point-plane configuration can be calculated using a formula [1] that transforms hyperbolic coordinates into Cartesian coordinates as follows,

$$E(x,y,z)=\frac{\left[V/\ln\left(\frac{2}{\varepsilon}\right)\right]}{\sqrt{c^2\cos^4\xi+x^2+y^2}}, \tag{1}$$

where the hyperbolic coordinates (η,ξ,ψ) relate to the 3D Cartesian coordinates as follows [1]:

$$x=-c\cos\xi\sinh\eta\sin\psi\ ;\quad y=-c\cos\xi\sinh\eta\cos\psi\ ;\quad z=c\sin\xi\cosh\eta\ , \tag{2}$$

where [1]

$$\cos^2\xi=\frac{u+\sqrt{u^2+4c^2\left(x^2+y^2\right)}}{2c^2}, \tag{3}$$

and [1]

$$u=c^2-\left(x^2+y^2+z^2\right)=c^2\cos^2\xi-\frac{\left(x^2+y^2\right)}{\cos^2\xi}, \tag{4}$$

and *V* is the input voltage.

To calculate certain positions on the plate without the needle against the needle tip position, we perform the calculation as if the upper part of Fig. 1.a only has one needle at position (2, 2) in Fig. 1.c. The position without a needle is designated as (•), whereas the position with a needle is assigned as (×), as shown in Fig. 2.a, for a 2D representation in the *xz* coordinates. However, seen from the z-axis, both position marks (•) and (×) for coordinate (2, 2) will coalesce as A_{00}. Therefore, a combination of those two marks in Fig. 2.b can simply be assigned as (×).

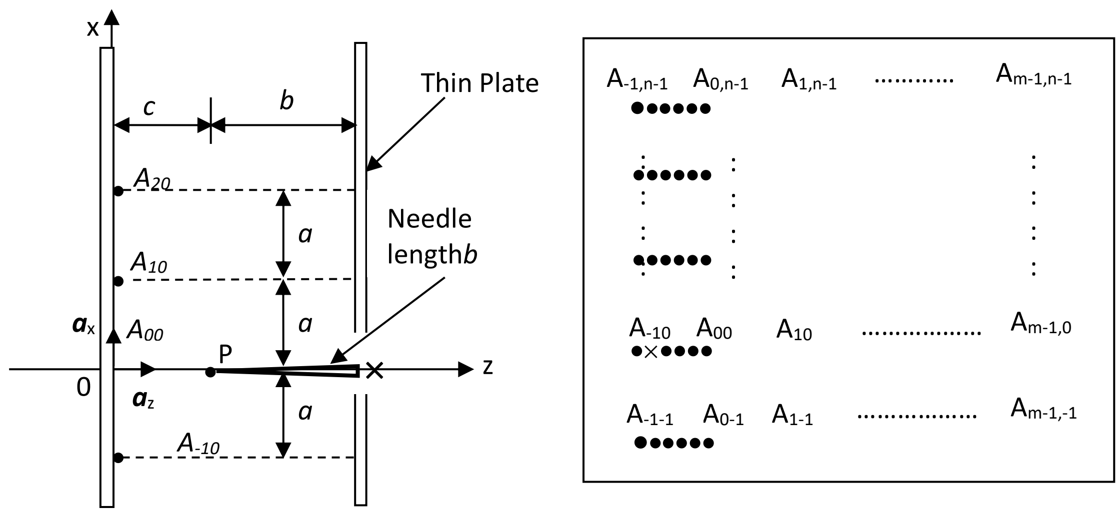


Figure2. a); Description of P points, A_{00}, A_{10}, A_{20} (marked •) on the 2D xz-plane (y = 0 and $z = \varsigma$, $\varsigma \ll 1$) that is induced by the electric current from the point-plane electrodes located in the positions marked (×). b); Full description of the points on the xy-plane from the z point of view without taking P into account; A_{-10}, A_{00}, A_{10}, etc. Observed from z, the position of A_{00} (•) coalesces with needle position (×), so that mark × is sufficient.

In Fig.2.a, a needle of length b (ending at point P), is attached on the plate (marked ×). The other points; (A_{00}, A_{10}, A_{20}, ...) are at a distance of $b+c$ from the plate with the needle, or points A_{00}, A_{10}, A_{20}, ...have a distance of $z = \varsigma$; $\varsigma \ll 1$ from the x-axis, where c is the distance from the needle tip to the plate without the needle.

The electric field generated by a needle electrode voltage source at point P with the coordinate $\xi = \frac{1}{2}\pi - \varepsilon$, where $\varepsilon \ll 1$, and η = 0 (as x = y = 0, z~c, u~0), can be expressed similarly to equation [1]:

$$E_P = E\left(\xi = \tfrac{1}{2}\pi - \varepsilon, \eta = 0\right) = \frac{\left[V / \ln\left(\frac{2}{\varepsilon}\right)\right]}{c\cos^2\left(\frac{1}{2}\pi - \varepsilon\right)}, \tag{5}$$

where the relationship of the coordinate η and variables x and y is defined as follows [1]:

$$\eta = \tanh^{-1}\left\{ \frac{\sqrt{x^2 + y^2}}{z} \tan\left(\tfrac{1}{2}\pi - \varepsilon\right) \right\}. \tag{6}$$

Equation (6) indicates a high electric field at the needle tip (point P); due to the value of $\cos^2\left(\tfrac{1}{2}\pi - \varepsilon\right) \ll 1$.

For the case at point A_{00} on the z-axis, with the distance c at the needle tip and its position at $z = \varsigma\,;\, \varsigma \ll 1\,; z \to 0$, the resulting electric field at point A_{00} at position $x = y = 0$ or $\eta = 0$; is [1] as follows:

$$E_{00}\left(x = y = 0,\, z\right) = \lim_{z \to 0} \frac{\left[cV / \ln\left(\tfrac{2}{\varepsilon}\right) \right]}{\left(c^2 - z^2\right)}. \tag{7}$$

At another point $A_{\mu\nu}$ with $x = \mu a$ and $y = \nu a$; $\mu, \nu = 0, \pm 1, \pm 2, \ldots$, the electric field induced by a point-plane electrode voltage source with the needle coalescing with the z-axis and its point at point P; is as follows:

$$E_{\mu\nu}\left(x = \mu a, y = \nu a, z = \varsigma\right) = \frac{\left[2cV / \ln\left(\tfrac{2}{\varepsilon}\right) \right]}{\sqrt{U_{\mu\nu}{}^2 + 4\left(\mu^2 + \nu^2\right)c^2 a^2}}, \tag{8}$$

where

$$U_{\mu\nu} = 2c^2 \cos^2 \xi = u_{\mu\nu} + \sqrt{u_{\mu\nu}{}^2 + 4c^2 a^2 \left(\mu^2 + \nu^2\right)} \;\;, \tag{9}$$

and

$$u_{\mu\nu} = \lim_{z \to 0} \left[c^2 - \left(x^2 + y^2 + z^2\right) \right] = \lim_{z \to 0} \left[c^2 - \left(\mu^2 + \nu^2\right) a^2 - z^2 \right]. \tag{10}$$

The following commutative relationship with absolute value applies;

$$E_{\mu\nu} = E_{\nu\mu} = E_{|\mu||\nu|};\, U_{\mu\nu} = U_{\nu\mu} = U_{|\mu||\nu|};\, u_{\mu\nu} = u_{\nu\mu} = u_{|\mu||\nu|}. \tag{11}$$

3. Electric Field Superposition

When there are $m \times n$ needle electrodes inducing a homogeneous electric field at certain points (Fig. 1.c), then the electric field inducing those points can be calculated using the concept of the electric field vector superposition that stems from those needles. In general, the magnitude of the electric field for points at $z = \zeta$, such as A_{00}, A_{20}, A_{14}, and so on. The calculation for the individual vector electric field where $x = \mu a$, $y = \nu a$ and $z = \zeta << 1$, is as follows:

$$\mathbf{E}_{\mu\nu}\left(x,y,z\right) = E_{\mu\nu}\left(\mu a, \nu a, \varsigma\right)\frac{\left\{x_N\mathbf{a}_x + y_N\mathbf{a}_y - c\mathbf{a}_z\right\}}{\sqrt{{x_N}^2 + {y_N}^2 + c^2}}, \tag{12}$$

where x_N, y_N and $z_N = -c$, which is the length of a 3D vector from the needle tip to certain positions (M, N) (Fig. 1.b). The electric field on the plate without a needle (plane xy) will be calculated (point A_{00} is always at distance c from the needle tip). The total electric field at point (M, N) is a superposition of the individual electric fields that consists of $A \times B$ needle electrodes that induce the point (M, N), with $m \times n$ being the total number of needles; hence, $A \times B \leq m \times n$; can be written as follows:

$$\left(\mathbf{E}_T\right)_{\mathbf{MN}} = \sum_{\mu=0}^{A-1}\sum_{\nu=0}^{B-1}\mathbf{E}_{\mu\nu}\left(x,y,z\right), \qquad M = 1,2,...,m. \quad \text{and} \qquad N = 1,2,...,n. \tag{13}$$

Some indexing rules apply:

1. The index (M, N) is a fixed position index on the xy-plane that relates to the number of needles ($m \times n$).
2. The index μ, ν is the variable position index from point coordinate A_{ij} at position ($x = \mu a$, $y = \nu a$, $z = \zeta$) from the central coordinate (0, 0, 0) point of view, in which the reference point A_{00} is a position at distance$c$from the needle tipat the fixed index needle position (M, N).
3. The notations x_N, y_N and $z_N = -c$ are vector coordinates of the needle positions that stem from the needle tips and end at the points where the electric field is calculated on the plate without a needle (xy-plane).

The total electric field at certain positions (M, N) at distance c from the tip of the needles induced by the electric field generated by $A \times B$ needle electrodes (the total number of which is $m \times n$), based on equation (13) is as follows:

$$\left(\mathbf{E}_T\right)_{\mathbf{MN}} = \sum_{\mu=0}^{A-1}\sum_{\nu=0}^{B-1}\left[E_{|M-1-\mu|,|N-1-\nu|}\right]_{\mu+1,\nu+1}\frac{\left\{\left(M-1-\mu\right)a\mathbf{a}_x + \left(N-1-\nu\right)a\mathbf{a}_y - c\mathbf{a}_z\right\}}{\sqrt{\left(\left(M-1-\mu\right)a\right)^2 + \left(\left(N-1-\nu\right)a\right)^2 + c^2}}, \tag{14}$$

where $M = 1, 2, 3, ..., m$ and$N = 1, 2, 3, ... , n$. This equation has electric field notation $E_{|M-1-\mu|,|N-1-\nu|}$ that which relates to equation (11).

We can consider that there is an arrangement of $m \times n$ needle electrodes as shown in Fig. 1.c. To calculate the electric field produced by each needle, at distance $c$from the needle tip, equation (14) is used. On the other hand, to calculate the total electric current produced by all needles, vector addition from each electric field unit in equation (14) must be performed. The total electric field resulting from all needles on the *x*- and *y*-axes will cancel each other out due to the symmetrical property, and what is left is the electric field components on the *z*-axis that will later be calculated.

Equation (14) describes the electric field resulting from the ions flow to the points at distances $x_\alpha = \alpha a$ and $y_\beta = \beta a$, with $\alpha = 0, 1, 2, \ldots, A\text{-}1$ and $\beta = 0, 1{,}2, \ldots, B\text{-}1$, where A and B are the maximum points on the plate surface that exposed by the ion current at the x and y coordinates, respectively, in discrete numbers. These ion currents will flow from the needle tip to the plate surface with the maximum plate area of $xy = (A\text{-}1)(B\text{-}1)a^2$. Because the ion current flux has symmetrical, homogeneous, and continuous properties in the plane configuration, the discrete characteristics (summation form) in equation (14) become the continuous characteristics (integration form) of the electric field quantity that can be solved using equation (15) ;

$$\left(E_z\right)_{m\times n} = \frac{c}{a^2}\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1}\int_{x=0}^{a\alpha} dx_\alpha \int_{y=0}^{a\beta} dy_\beta \frac{\left[VK_{|\alpha||\beta|}/\ln\left(\frac{2}{\varepsilon}\right)\right]}{\left(x_\alpha{}^2 + y_\beta{}^2 + c^2\right)}. \tag{15}$$

Substitution from 2D Cartesian coordinates to the polar coordinates results in the following:

$$\left(E_z\right)_{m\times n} = \frac{c}{a^2}\left[\frac{VK_{|\alpha||\beta|}}{\ln\left(\frac{2}{\varepsilon}\right)}\right]\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1}\int_{\rho=0}^{a\sqrt{\alpha^2+\beta^2}} \frac{\rho_{\alpha\beta}}{\left(\rho_{\alpha\beta}{}^2 + c^2\right)} d\rho_{\alpha\beta}\int_{\phi=0}^{2\pi} d\phi, \quad \rho_{\alpha\beta}{}^2 = x_\alpha{}^2 + y_\beta{}^2, \tag{16}$$

and this generates the electric field given by the following:

$$\left(E_z\right)_{m\times n} = \frac{\pi c}{a^2}\left[\frac{V}{\ln\left(\frac{2}{\varepsilon}\right)}\right]\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1} K_{|\alpha||\beta|} \ln\left|\frac{a^2\left(\alpha^2+\beta^2\right)+c^2}{c^2}\right|. \tag{17}$$

4. Angle of Plasma Ion Flow

We note that not all points at positions $A_{\mu\nu}$;$\mu, \nu = 0, \pm1, \pm2, \ldots$, can be induced by the electric field. According to Nur et al. [8], the angular deviation of the plasma ion flow from the point location induced by the electric field to the perpendicular direction of the needle is around 60°, up to a maximum of 67°, as shown in Fig. 3.

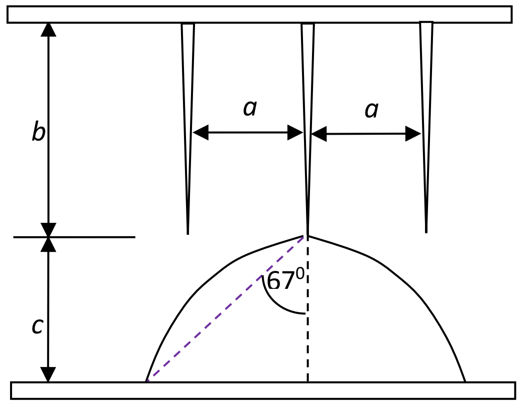


Figure 3. Maximum angular deviation of the electric field from the induced point location to the perpendicular direction of the needle is around 67°.

The relationship of θ and the position $A_{|\alpha||\beta|}$ can be calculated with the following equation:

$$\theta = \tan^{-1}\left\{\frac{a}{c}\sqrt{\alpha^2+\beta^2}\right\} \leq 67^o, \text{ at position } A_{|\alpha||\beta|}. \tag{18}$$

To verify the numerical simulations, we conducted an experiment to determine the relationship between the electric current I and voltage source V using a plasma discharge with multipoint-plane configuration, which has been performed at the Radiation Physics Laboratory at Diponegoro University. The needles were arranged in an 8 × 4 = 32 needle formation with a = 0.8068 cm, b = 0.018 cm and c was varied at 1 cm ; 2 cm ; 3 cm and 4 cm. The overall value of $K_{\alpha\beta}$ for the 8 × 4 needle configuration is as follows:

$$K_{00} = 32 \text{ ; } K_{|0||\beta|} = K_{|\alpha||0|} = 64 \text{ and } K_{|\alpha||\beta|} = 128 \text{ for } \alpha, \beta = 1, 2, \ldots, 7. \tag{19}$$

The values of $A_{|\alpha||\beta|}$, index couple (α, β); and position number $K_{|\alpha||\beta|}$ for each variation of c, (taking equation (18) into account); are given in Table 1;

Table 1. Values of position $A_{|\alpha||\beta|}$, index couple (α, β), and position number $K_{|\alpha||\beta|}$ for varied c.

No.	c	Position	(α, β)	$K_{|\alpha||\beta|}$
1.	1 cm	A_{00}, $A_{|0||1|}$, $A_{|1||0|}$, $A_{|1||1|}$, $A_{|1||2|}$, $A_{|2||1|}$, $A_{|2||2|}$	(0,0) ; (0,1) ; (1,0); (1,1) ; (1, 2) ; (2,1) ; (2, 2).	$K_{|0||0|}$, $K_{|0||1|}$, $K_{|1||0|}$, $K_{|1||1|}$, $K_{|1||2|}$, $K_{|2||1|}$, $K_{|2||2|}$.
2.	2 cm	$A_{|0||0|}$, … , $A_{3||3|}$, $A_{|3||4|}$	(0,0) ; (0,1) ; (1,0) ; …. ;	$K_{|0||0|}$, … , $K_{|3||3|}$, $K_{|3||4|}$,

		, $A_{\|3\|\|5\|}$, $A_{\|4\|\|3\|}$, $A_{\|5\|3\|}$.	(3,3) ; (3, 4) ; (3,5) ; (4, 3) ; (5, 3).	$K_{\|3\|\|5\|}$, $K_{\|4\|3\|}$, $K_{\|5\|3\|}$.
3.	3 cm	A_{00} , $A_{\|0\|\|1\|}$, $A_{\|1\|\|0\|}$, $A_{\|1\|\|1\|}$, ..., $A_{\|6\|\|6\|}$, $A_{\|7\|\|6\|}$, $A_{\|6\|\|7\|}$	(0,0) ; (0,1) ; (1,0) ; …. ; (6,6) ; (7, 6) ; (6,7).	$K_{\|0\|\|0\|}$, $K_{\|0\|\|1\|}$, $K_{\|1\|\|0\|}$, ... , $K_{\|6\|\|6\|}$, $K_{\|7\|6\|}$, $K_{\|6\|\|7\|}$.
4.	4 cm	A_{00} , $A_{\|0\|\|1\|}$, $A_{\|1\|\|0\|}$, $A_{\|1\|\|1\|}$, ..., $A_{\|7\|\|6\|}$, $A_{\|6\|\|7\|}$, $A_{\|7\|\|7\|}$	(0,0) ; (0,1) ; (1,0) ; …. ; (6,6) ; (7, 6) ; (6,7) ; (7,7).	$K_{\|0\|\|0\|}$, $K_{\|0\|\|1\|}$, $K_{\|1\|\|0\|}$, ... , $K_{\|6\|\|6\|}$, $K_{\|7\|6\|}$, $K_{\|6\|\|7\|}$, $K_{\|7\|\|7\|}$.

5. Induced Current

In the case of the point-plane configuration, the charge Q induced on the plane electrode becomes [1] the following;

$$Q = \frac{V(\xi) - V}{V} q, \tag{20}$$

where V is the potential of the point electrode and q is the charge of the electric flux lines coming from the multipoint to the plane configuration as defined in equation (20), and the induced current yields the following:

$$i = -\frac{dQ}{dt} = -\frac{q}{V}\frac{dV(\xi)}{ds}\frac{ds}{dt} = \mu_0 \frac{q}{V} E^2. \tag{21}$$

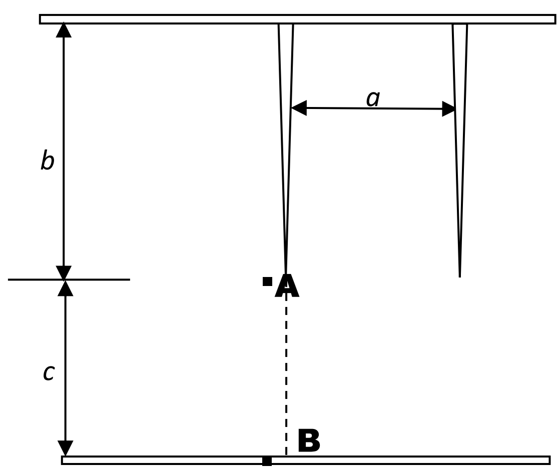


Figure 4. Electric field calculation on the plane electrode (B) positioned at distance c from the point electrode (A).

According to Halliday et al.[16], the electric field strength at point B can be written as follows:

$$E_Q = \frac{q}{4\pi\varepsilon_0 c}\frac{1}{(b+c)} \quad . \tag{22}$$

When the results from the work by Coelho and Debeau [1] are used as a comparison, the electric field strength at B located at distance c from the point electrode can be written as follows:

$$E_Q \cong \frac{V}{c\ln\left(\frac{2}{\in}\right)} \quad . \tag{23}$$

Using equations (22) and (23), charge q is yielded as follows:

$$q = \frac{4\pi\varepsilon_0 (b+c)V}{\ln\left(\frac{2}{\in}\right)} \quad . \tag{24}$$

The electric current from the multipoint-plane configuration with 32 needles (N = 32) can be calculated using the equations (17), (21), and (24) as follows:

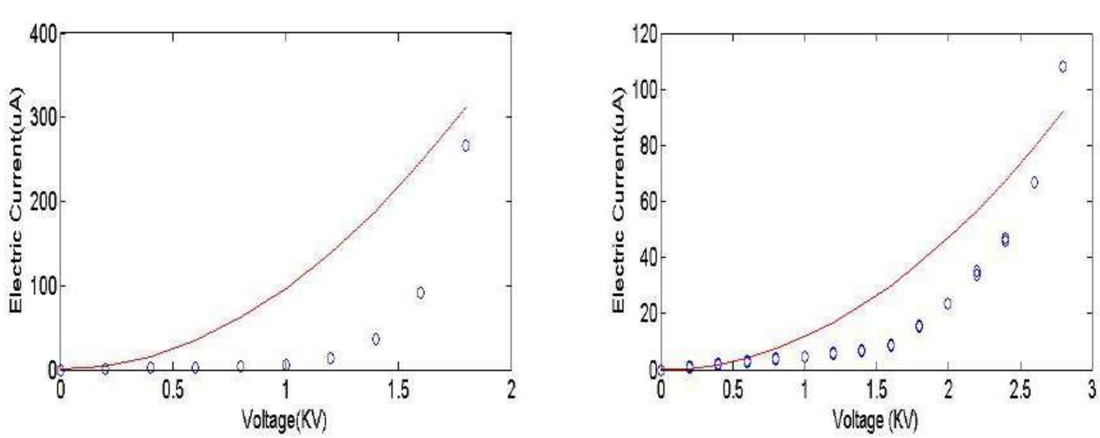
$$i = -N\frac{dQ}{dt}$$

$$= \mu_0 N \frac{4\pi^3\varepsilon_0 (b+c)c^2V^2}{a^4\ln^3\left(\frac{2}{\in}\right)}\left\{\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1}K_{|\alpha||\beta|}\ln\left|\frac{a^2\left(\alpha^2+\beta^2\right)+c^2}{c^2}\right|\right\}^2 \quad \text{with} \quad \in <<< 1, \tag{25}$$

where μ_0 and ε_0 are the mobility ($4\pi \times 10^{-7}$Wb/A.m) and permittivity ($8{,}85 \times 10^{-12}$ F/m) at the vacuum space, respectively.

6. Results and Discussion

In the simulation graphs for the electric current I and voltage V, we use Table 1 and equation (25) for different values of c (1, 2, 3 and 4 cm). These simulation graphs are compared with experiment graphs of the same variations ofelectric current I and voltage V ;



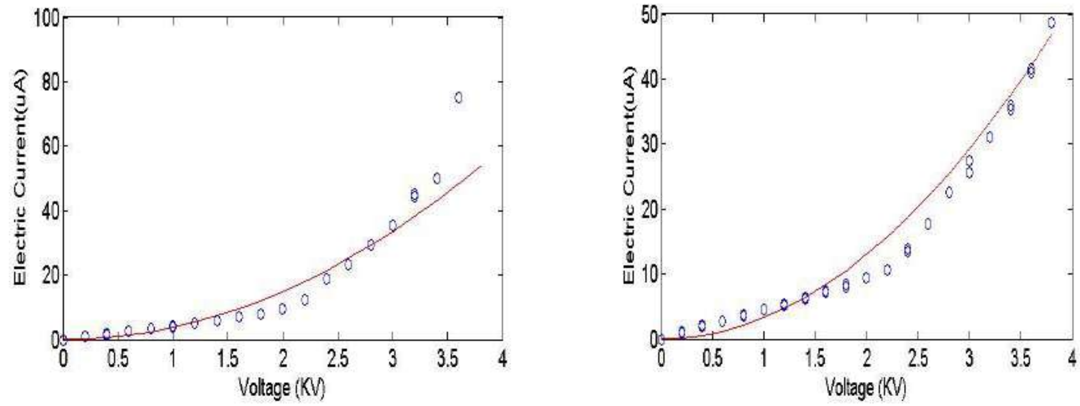


Figure 5. Graphs of the relationship between the electric current *I* and voltage source *V* obtained from the 8 × 4 = 32 needle electrode configuration, limited to 67° for the maximum deviation angle for*a* = 0,8068 cm, *b*= 0.018 cm, and varied *c* at 1; 2; 3 and 4 cm. Blue circles indicate the experiment results. Red lines show simulation results from equation (25).

A theory of corona discharge with multipoint-plane configuration has been discussed. The calculations of the electric field and saturated current generated from this configuration when input voltage *V* is applied have also been elaborated. The calculation of the total electric field resulting from $m \times n$ needle electrodes must be done using the concept of the electric field vector superposition. This research employs an arrangement of 8×4 needle electrodes with varied distances between the point-to-plane electrodes (*c*) at 1, 2, 3, and 4 cm.

The resulting graphs show that the simulation results are closer to the experiment results when the distance *c* is larger, especially for *c* at 3 cm and 4 cm. A narrower *c* causes an asymmetrical and inhomogeneous ion flow in which some areas are flooded with more ions than predicted. For a higher*c*, the symmetrical and homogeneous ion flow is closer to the experimental results. This causes an electric current reading that is closer to the expected value. Moreover, a narrower *c* does not allow the maximum electric field deviation angle from the induced point location to the perpendicular needle position, which may reach 67°, while greater *c*allows this to take place, hence, almost all ion flow that stems from the needle electrodes reaches all the designated points on the plane without the needles, and in turn, yields a greater electric field. Another influencing factor for the electric current reading is the shape of the needle with a sharpness no closer than 0°, which is the ideal condition for electric field calculation.

These statements can be explained as follows, Equation (14) shows the 3D vector of the ion current flow model that flows from the needle tip to the bottom plate with a parabolic shape as shown in Fig. 3. To simplify equation (14), we assume that the ion current flows symmetrically so that the flowing 3D vector will be changed to one direction in the upright axis (z-axis) because the ion current direction at the xy-plane will be a symmetrical circle; therefore, it will eliminate the others. Another assumption is that the ion current in the direction of the z-axis will be homogenously distributed and close to continuously flowing, so that the vector and discrete (summation) characteristics in equation (14) are changed to continuous (integration) and scalar characteristics (only in the direction of the z-axis) in equation (15), where equation (15) is part of equation (25). Therefore, the conditions of homogenous continuity and symmetry will be better for an increased distance from the multipoint-plane to the bottom plate surface, so that the mathematical simulation will match the results of the experiment at a greater value of c.

7. Conclusion

The current-voltage (*I-V*) characteristics that were produced by the corona discharge plasma generator for the multipoint-plane configuration in the air could demonstrate the performance of a device. The total electric field inducing these points could be calculated using the concept of the electric field vector superposition that stems from these needles. The total number of needles in this configuration is $8 \times 4 = 32$, and there is a variation of distance c, which is the distance between the point-to-plane electrodes. The between the numerical simulation and experimental results indicated that the *I-V* characteristic curve is simulated better for longer distances between the point-to-plane electrodes, which is roughly longer than 3 cm; due to better symmetry and homogeneity of the ion current flows from the multipoint-plane to the plane configuration.

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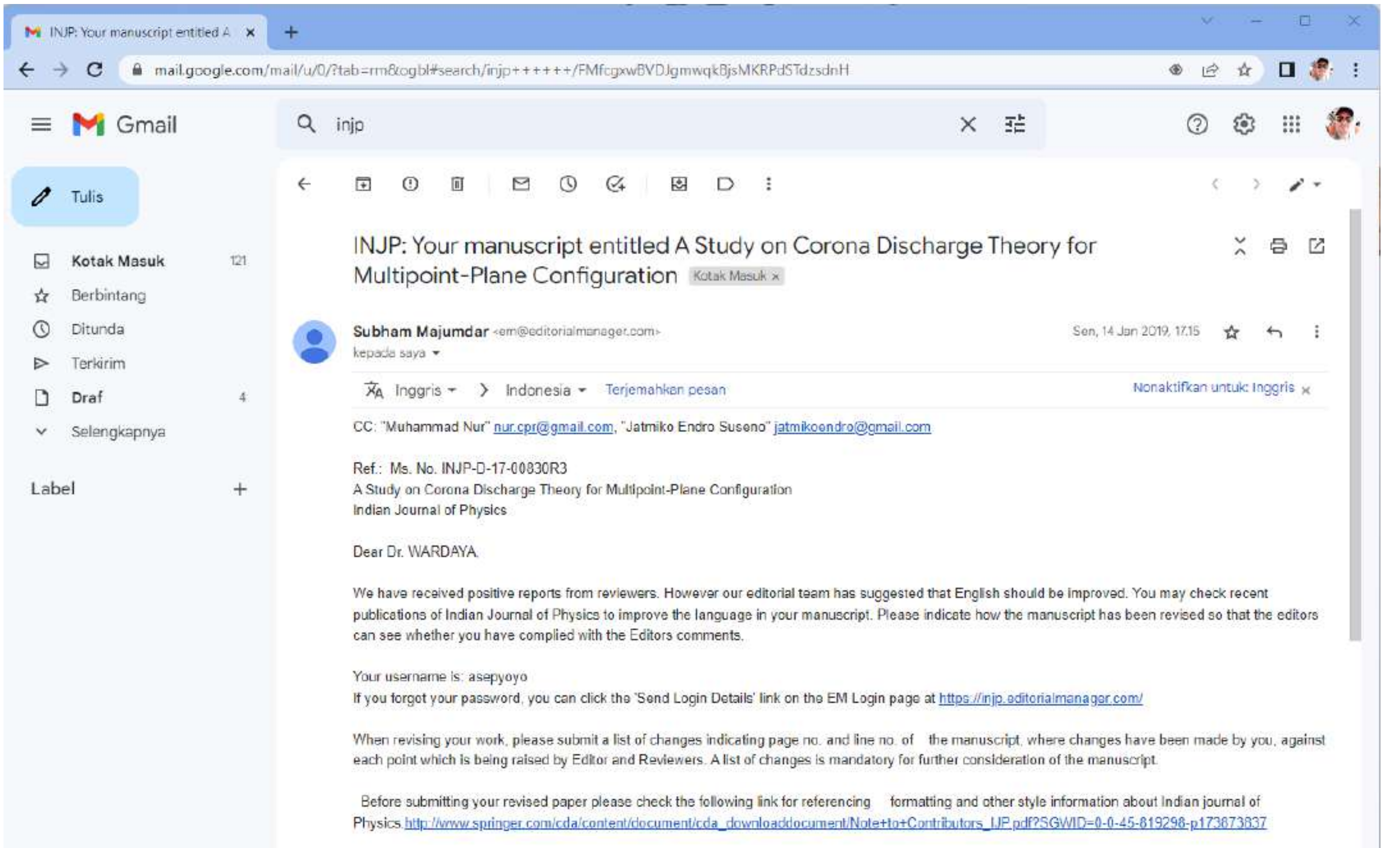

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ORIGINAL PAPER

A study of the corona discharge theory for multipoint–plane configurations

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Abstract: This paper presents the numerical calculation of current–voltage (*I–V*) characteristics that were produced by a corona discharges plasma generator for a multipoint–plane configuration in air and its comparison with the experimental results. The total number of needles in this configuration is $8 \times 4 = 32$ with the distance between the point-to-plane electrodes (denoted as *c*) as the variable. The *I–V* characteristic curve of the numerical calculation results matches that of the experimental results for cases with a large distance *c* ($c = 3$ and 4 cm), and it shows a large deviation for cases with a small distance *c* ($c = 1$ and 2 cm). Differences in the *I–V* characteristic curve between the experimental and numerical results are due to the symmetrical spread of the ion current from the point-to-plane electrodes, which is more pronounced for larger values of *c*.

Keywords: Plasma generator; Multipoint–plane configuration; Electric field; Electric current; *I–V* characteristics

PACS Nos.: 02.30.−f; 02.30.Em; 02.30.Ik; 02.30.Mv; 02.70.−c

1. Introduction

The corona discharge technique has been widely used for various research studies. Some of the papers on various electrode model configurations of corona discharges that try to obtain potential, voltage, or electric current characteristic values include the tip–plane configuration [1], thin bar–needle configuration [2], cylinder–wire–plate configuration [3], sub-millimeter electrode gap configuration [4], point-to-ring configuration [5], and multipoint–plane configuration [6]. However, this paper discusses the current–voltage characteristics from the experimental results. Some other research studies have calculated values related to corona discharges, among which are electrical potential distribution of pin-multi-ring concentric electrodes [7], electrohydrodynamic and wind-ion direction produced by plasma discharge [8], ionic wind generation of needle-to-cylinder electrode model [9], ionic wind generation of multi-electrode model [10], electro hydrodynamic force by a corona discharge [11].

There are also research studies that discuss the direct application of the corona discharge electrode configuration; cold large-diameter plasma jet of a triple electrode model [12], electric potential distribution of various electrode models [13], and laser-induced streamer corona discharge of a needle-to-plate electrode model [14].

This research is considered an extension of the work reported by Jaworek and Krupa [6] for the case of comparing the numerical calculation and experimental results of voltage and electric current characteristics generated by a corona discharge from plasma electrodes using a multipoint configuration. According to Sigmond [15], a large electric field generation along with a saturated current in the form of a corona discharge that in turn produces corona plasma which is due to the sharp end of one of the electrodes and the asymmetrical shape of both electrodes.

In this study, we use a model of a multipoint–plane configuration that consists of two perpendicular plates on one of which $m \times n$ number of needles is attached, as shown in Fig. 1.

As seen in Fig. 1, the needle length is *b*, inter-needle space is *a,* and distance between the point-to-plane electrodes is *c*. Hence, the distance between the two thin plates

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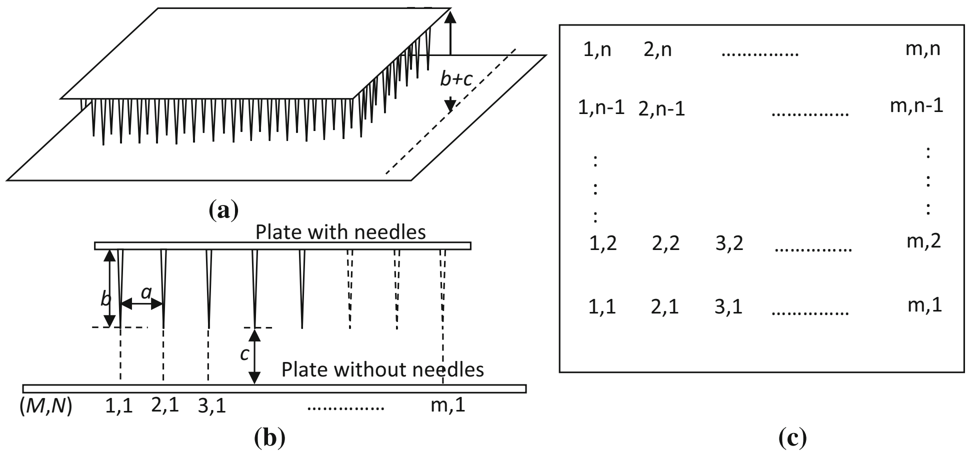

Fig. 1 Model of the multipoint–plane configuration consisting of two parallel plates on one of which $m \times n$ needles are attached. The inter-needle distance is a, needle length is b, and distance between the point-to-plane electrodes is c. (**a**). 3D representation of the electrode model. (**b**). Side view of the electrode model. (**c**). Top view of the location of $m \times n$ needles (marked $\times$)

is $b + c$. The experiment of the corona discharge for the multipoint–plane configuration uses DC voltage; with a positive polarity position at the point position and negative polarity at the plane position.

2. Electric field intensity

The electric field generated by the corona discharge from the point–plane configuration can be calculated using a formula [1] that transforms hyperbolic coordinates into Cartesian coordinates as follows:

$$E(x, y, z) = \frac{[V/\ln(\frac{2}{\varepsilon})]}{\sqrt{c^2\cos^4\xi + x^2 + y^2}}, \tag{1}$$

where the hyperbolic coordinates (η, ξ, ψ) relate to the 3D Cartesian coordinates as follows [1]:

$$x = -c\cos\xi\sinh\eta\sin\psi; \quad y = -c\cos\xi\sinh\eta\cos\psi; \quad z = c\sin\xi\cosh\eta, \tag{2}$$

where [1]

$$\cos^2\xi = \frac{u + \sqrt{u^2 + 4c^2(x^2 + y^2)}}{2c^2}, \tag{3}$$

and [1]

$$u = c^2 - \left(x^2 + y^2 + z^2\right) = c^2\cos^2\xi - \frac{(x^2 + y^2)}{\cos^2\xi}, \tag{4}$$

and V is the input voltage.

To calculate certain positions on the plate without the needle against the needle tip position, we perform the calculation as if the upper part of Fig. 1.a only has one needle at position (2, 2) in Fig. 1.c. The position without a needle is designated as "filled circle," whereas the position with a needle is assigned as $\times$, as shown in Fig. 2.a, for a 2D representation in the xz coordinates. However, seen from the z-axis, both position marks "filled circle" and $\times$ for coordinate (2, 2) will coalesce as A_{00}. Therefore, a combination of those two marks in Fig. 2.b can simply be assigned as ($\times$).

In Fig. 2.a, a needle of length b (ending at point P) is attached on the plate (marked $\times$). The other points (A_{00}, A_{10}, A_{20}, …) are at a distance of $b + c$ from the plate with the needle, or points A_{00}, A_{10}, A_{20}, … have a distance of $z = \varsigma; \varsigma \ll 1$ from the x-axis, where c is the distance from the needle tip to the plate without the needle.

The electric field generated by a needle electrode voltage source at point P with the coordinate $\xi = \frac{1}{2}\pi - \varepsilon$, where $\varepsilon \ll 1$, and $\eta = 0$ (as $x = y = 0$, $z \sim c$, $u \sim 0$), can be expressed similarly to equation [1]:

$$E_P = E\left(\xi = \frac{1}{2}\pi - \varepsilon, \eta = 0\right) = \frac{[V/\ln(\frac{2}{\varepsilon})]}{c\cos^2(\frac{1}{2}\pi - \varepsilon)}, \tag{5}$$

where the relationship of the coordinate η and variables x and y is defined as follows [1]:

$$\eta = \tanh^{-1}\left\{\frac{\sqrt{x^2 + y^2}}{z}\tan\left(\frac{1}{2}\pi - \varepsilon\right)\right\}. \tag{6}$$

Equation (6) indicates a high electric field at the needle tip (point P) due to the value of $\cos^2(\frac{1}{2}\pi - \varepsilon) \ll 1$.

For the case at point A_{00} on the z-axis, with the distance c at the needle tip and its position at $z = \varsigma; \varsigma \ll 1; z \to 0$, the resulting electric field at point A_{00} at position $x = y = 0$ or $\eta = 0$ is [1] as follows:

$$E_{00}(x = y = 0, z) = \lim_{z \to 0}\frac{[cV/\ln(\frac{2}{\varepsilon})]}{(c^2 - z^2)}. \tag{7}$$

At another point $A_{\mu\nu}$ with $x = \mu a$ and $y = \nu a$, $\mu,\nu = 0, \pm 1, \pm 2, \ldots$, the electric field induced by a point–plane electrode voltage source with the needle coalescing with the z-axis and its point at point P is as follows:

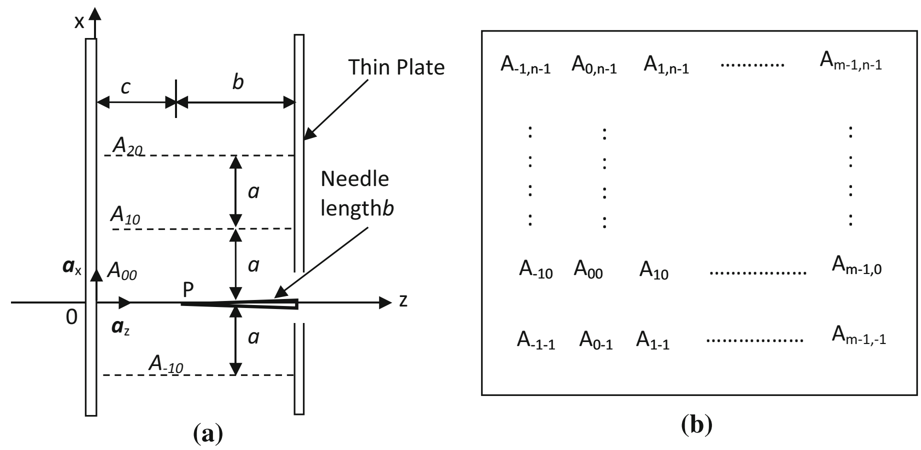

Fig. 2 (**a**) Description of P points, A_{00}, A_{10}, A_{20} (marked "filled circle") on the 2D xz-plane ($y = 0$ and $z = \varsigma$, $\varsigma \ll 1$) that is induced by the electric current from the point–plane electrodes located in the positions marked (×). (**b**) Full description of the points on the xy-plane from the z point of view without taking P into account, A_{-10}, A_{00}, A_{10}, etc. Observed from z, the position of A_{00} ("filled circle") coalesces with needle position (×), so that mark × is sufficient

$$E_{\mu\nu}(x = \mu a, y = \nu a, z = \varsigma) = \frac{[2cV/\ln(\frac{2}{\varepsilon})]}{\sqrt{U_{\mu\nu}^2 + 4(\mu^2 + \nu^2)c^2a^2}}, \tag{8}$$

where

$$U_{\mu\nu} = 2c^2\cos^2\xi = u_{\mu\nu} + \sqrt{u_{\mu\nu}^2 + 4c^2a^2(\mu^2 + \nu^2)}, \tag{9}$$

and

$$\begin{aligned} u_{\mu\nu} &= \lim_{z\to 0}\left[c^2 - \left(x^2 + y^2 + z^2\right)\right] \\ &= \lim_{z\to 0}\left[c^2 - \left(\mu^2 + \nu^2\right)a^2 - z^2\right]. \end{aligned} \tag{10}$$

The following commutative relationship with absolute value applies

$$\begin{aligned} &E_{\mu\nu} = E_{\nu\mu} = E_{|\mu||\nu|}; \quad U_{\mu\nu} = U_{\nu\mu} = U_{|\mu||\nu|}; \\ &u_{\mu\nu} = u_{\nu\mu} = u_{|\mu||\nu|}. \end{aligned} \tag{11}$$

3. Electric field superposition

When there are $m \times n$ needle electrodes inducing a homogeneous electric field at certain points (Fig. 1c), the electric field inducing those points can be calculated using the concept of the electric field vector superposition that stems from those needles. In general, the magnitude of the electric field can be used for all points at $z = \zeta$, therefore the calculation for the individual vector electric field where $x = \mu a$, $y = \nu a$ and $z = \zeta << 1$, is as follows:

$$\mathbf{E}_{\mu\nu}(x, y, z) = E_{\mu\nu}(\mu a, \nu a, \varsigma)\frac{\{x_N\mathbf{a}_x + y_N\mathbf{a}_y - c\mathbf{a}_z\}}{\sqrt{x_N^2 + y_N^2 + c^2}}, \tag{12}$$

where x_N, y_N, and $z_N = -c$, which is the length of a 3D vector from the needle tip to certain positions (M, N) (Fig. 1.b). The electric field on the plate without a needle (plane xy) will be calculated. (Point A_{00} is always at distance c from the needle tip.) The total electric field at point (M, N) is a superposition of the individual electric fields that consist of $A \times B$ needle electrodes that induce the point (M, N), with $m \times n$ being the total number of needles; hence, $A \times B \leq m \times n$ can be written as follows:

$$(\mathbf{E}_T)_{\mathbf{MN}} = \sum_{\mu=0}^{A-1}\sum_{\nu=0}^{B-1}\mathbf{E}_{\mu\nu}(x, y, z), \quad M = 1, 2, \ldots, m. \quad \text{and} \quad N = 1, 2, \ldots, n. \tag{13}$$

Some indexing rules apply:

1. The index (M, N) is a fixed position index on the xy-plane that relates to the number of needles ($m \times n$).
2. The index μ,ν is the variable position index from point coordinate A_{ij} at position ($x = \mu a$, $y = \nu a$, $z = \zeta$) from the central coordinate (0, 0, 0) point of view, in which the reference point A_{00} is a position at distance c from the needle tip at the fixed index needle position (M, N).
3. The notations x_N, y_N, and $z_N = -c$ are vector coordinates of the needle positions that stem from the needle tips and end at the points where the electric field is calculated on the plate without a needle (xy-plane).

The total electric field at certain positions (M, N) at distance c from the tip of the needles induced by the electric field generated by $A \times B$ needle electrodes (the total number of which is $m \times n$) based on Eq. (13) is as follows:

$$(\mathbf{E}_T)_{\mathbf{MN}} = \sum_{\mu=0}^{A-1}\sum_{\nu=0}^{B-1}\left[E_{|M-1-\mu|,|N-1-\nu|}\right]_{\mu+1,\nu+1} \frac{\{(M-1-\mu)a\mathbf{a}_x + (N-1-\nu)a\mathbf{a}_y - c\mathbf{a}_z\}}{\sqrt{((M-1-\mu)a)^2 + ((N-1-\nu)a)^2 + c^2}}, \tag{14}$$

where $M = 1, 2, 3, \ldots, m$ and $N = 1, 2, 3, \ldots, n$. This equation has electric field notation $E_{|M-1-\mu|,|N-1-v|}$ which relates to Eq. (11).

We can consider that there is an arrangement of $m \times n$ needle electrodes as shown in Fig. 1.c. To calculate the electric field produced by each needle, at distance c from the needle tip, Eq. (14) is used. On the other hand, to calculate the total electric current produced by all needles, vector addition from each electric field unit in Eq. (14) must be performed. The total electric field resulting from all needles on the x- and y-axes will cancel each other out due to the symmetrical property, and what is left is the electric field components on the z-axis that will later be calculated.

Equation (14) describes the electric field resulting from the ions that flow to the points at distances $x_\alpha = \alpha a$ and $y_\beta = \beta a$, with $\alpha = 0, 1, 2, \ldots, A-1$ and $\beta = 0, 1,2, \ldots, B-1$, where A and B are the maximum points on the plate surface that exposed by the ion current at the x and y coordinates, respectively, in discrete numbers. These ion currents will flow from the needle tip to the plate surface with the maximum plate area of $xy = (A-1)(B-1)a^2$. Because the ion current flux has symmetrical, homogeneous, and continuous properties in the plane configuration, the discrete characteristics (summation form) in Eq. (14) become the continuous characteristics (integration form) of the electric field quantity that can be solved using Eq. (15);

$$(E_z)_{m\times n} = \frac{c}{a^2}\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1}\int_{x=0}^{a\alpha} \mathrm{d}x_\alpha \int_{y=0}^{a\beta} \mathrm{d}y_\beta \frac{\left[VK_{|\alpha||\beta|}/\ln\left(\frac{2}{\varepsilon}\right)\right]}{\left(x_\alpha^2 + y_\beta^2 + c^2\right)} \tag{15}$$

Substitution from 2D Cartesian coordinates to the polar coordinates results in the following:

$$(E_z)_{m\times n} = \frac{c}{a^2}\left[\frac{VK_{|\alpha||\beta|}}{\ln\left(\frac{2}{\varepsilon}\right)}\right]\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1}\int_{\rho=0}^{a\sqrt{\alpha^2+\beta^2}} \frac{\rho_{\alpha\beta}}{\left(\rho_{\alpha\beta}^2 + c^2\right)}\mathrm{d}\rho_{\alpha\beta}\int_{\phi=0}^{2\pi}\mathrm{d}\phi, \quad \rho_{\alpha\beta}^2 = x_\alpha^2 + y_\beta^2, \tag{16}$$

and this generates the electric field given by the following:

$$(E_z)_{m\times n} = \frac{\pi c}{a^2}\left[\frac{V}{\ln\left(\frac{2}{\varepsilon}\right)}\right]\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1} K_{|\alpha||\beta|} \ln\left|\frac{a^2\left(\alpha^2+\beta^2\right)+c^2}{c^2}\right|. \tag{17}$$

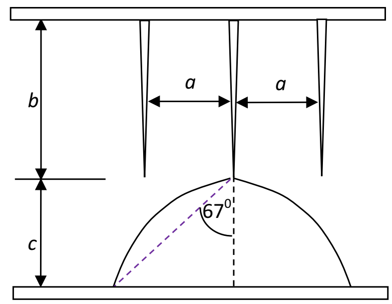

Fig. 3 Maximum angular deviation of the electric field from the induced point location to the perpendicular direction of the needle is around 67°

4. Angle of plasma ion flow

We note that not all points at positions $A_{\mu v}$, $\mu, v = 0, \pm 1, \pm 2, \ldots$ can be induced by the electric field. According to Nur et al. [8], the angular deviation of the plasma ion flow from the point location induced by the electric field to the perpendicular direction of the needle is around 60°, up to a maximum of 67°, as shown in Fig. 3.

The relationship of θ and the position $A_{|\alpha||\beta|}$ can be calculated with the following equation:

$$\theta = \tan^{-1}\left\{\frac{a}{c}\sqrt{\alpha^2+\beta^2}\right\} \le 67^\circ, \quad \text{at position } A_{|a||b|}. \tag{18}$$

To verify the numerical simulations, we conducted an experiment to determine the relationship between the electric current I and voltage source V using a plasma discharge with multipoint–plane configuration, which has been performed at the Radiation Physics Laboratory at Diponegoro University. The needles were arranged in an $8 \times 4 = 32$ needle formation with $a = 0.8068$ cm, $b = 0.018$ cm, and c was varied at 1 cm; 2 cm; 3 cm; and 4 cm. The overall value of $K_{\alpha\beta}$ for the 8×4 needle configuration is as follows:

$$K_{00} = 32; K_{|0||\beta|} = K_{|\alpha||0|} = 64 \text{ and } K_{|\alpha||\beta|} = 128 \text{ for } \alpha, \beta = 1, 2, \ldots, 7. \tag{19}$$

The values of $A_{|\alpha||\beta|}$ index couple (α, β) and position number $K_{|\alpha||\beta|}$ for each variation of c, [taking Eq. (18) into account] are given in Table 1.

5. Induced current

In the case of the point–plane configuration, the charge Q induced on the plane electrode becomes [1] the following:

Table 1 Values of position $A_{|\alpha||\beta|}$, index couple (α, β), and position number $K_{|\alpha||\beta|}$ for varied c

No.	C	Position	(α, β)	$K_{|\alpha||\beta|}$
1.	1 cm	$A_{00}, A_{|0||1|}, A_{|1||0|}, A_{|1||1|}, A_{|1||2|}, A_{|2||1|}, A_{|2||2|}$	$(0,0); (0,1); (1,0); (1,1); (1,2); (2,1); (2,2)$	$K_{|0||0|}, K_{|0||1|}, K_{|1||0|}, K_{|1||1|}, K_{|1||2|}, K_{|2||1|}, K_{|2||2|}$
2.	2 cm	$A_{|0||0|}, \ldots, A_{|3||3|}, A_{|3||4|}, A_{|3||5|}, A_{|4||3|}, A_{|5||3|}$	$(0,0); (0,1); (1,0); \ldots; (3,3); (3,4); (3,5); (4,3); (5,3)$	$K_{|0||0|}, \ldots, K_{|3||3|}, K_{|3||4|}, K_{|3||5|}, K_{|4||3|}, K_{|5||3|}$
3.	3 cm	$A_{00}, A_{|0||1|}, A_{|1||0|}, A_{|1||1|}, \ldots, A_{|6||6|}, A_{|7||6|}, A_{|6||7|}$	$(0,0); (0,1); (1,0); \ldots; (6,6); (7,6); (6,7)$	$K_{|0||0|}, K_{|0||1|}, K_{|1||0|}, \ldots, K_{|6||6|}, K_{|7||6|}, K_{|6||7|}$
4.	4 cm	$A_{00}, A_{|0||1|}, A_{|1||0|}, A_{|1||1|}, \ldots, A_{|7||6|}, A_{|6||7|}, A_{|7||7|}$	$(0,0); (0,1); (1,0); \ldots; (6,6); (7,6); (6,7); (7,7)$	$K_{|0||0|}, K_{|0||1|}, K_{|1||0|}, \ldots, K_{|6||6|}, K_{|7||6|}, K_{|6||7|}, K_{|7||7|}$

$$Q = \frac{V(\xi) - V}{V} q, \tag{20}$$

where V is the potential of the point electrode and q is the charge of the electric flux lines coming from the multipoint to the plane configuration as defined in Eq. (20), and the induced current yields the following (Fig. 4):

$$i = -\frac{dQ}{dt} = -\frac{q}{V}\frac{dV(\xi)}{ds}\frac{ds}{dt} = \mu_0 \frac{q}{V} E^2. \tag{21}$$

According to Halliday et al. [16], the electric field strength at point B can be written as follows:

$$E_Q = \frac{q}{4\pi\varepsilon_0 c}\frac{1}{(b+c)}. \tag{22}$$

When the results from the work by Coelho and Debeau [1] are used as a comparison, the electric field strength at B located at distance c from the point electrode can be written as follows:

$$E_Q \cong \frac{V}{c \ln\left(\frac{2}{\epsilon}\right)}. \tag{23}$$

Using Eqs. (22) and (23), charge q is yielded as follows:

$$q = \frac{4\pi\varepsilon_0 (b+c) V}{\ln\left(\frac{2}{\epsilon}\right)}. \tag{24}$$

The electric current from the multipoint–plane configuration with 32 needles (N = 32) can be calculated using Eqs. (17), (21), and (24) as follows:

$$\begin{aligned} i &= -N\frac{\mathrm{d}Q}{\mathrm{d}t} \\ &= \mu_0 N \frac{4\pi^3 \varepsilon_0 (b+c) c^2 V^2}{a^4 \ln^3\left(\frac{2}{\epsilon}\right)} \\ &\left\{\sum_{\alpha=0}^{A-1}\sum_{\beta=0}^{B-1} K_{|\alpha||\beta|} \ln\left|\frac{a^2\left(\alpha^2+\beta^2\right)+c^2}{c^2}\right|\right\}^2 \\ &\text{with} \quad \epsilon <<< 1, \end{aligned} \tag{25}$$

where μ_0 and ε_0 are the mobility ($4\pi \times 10^{-7}$ Wb/A.m) and permittivity (8.85×10^{-12} F/m) at the vacuum space, respectively.

6. Results and discussion

In the simulation graphs for the electric current I and voltage V, we use Table 1 and Eq. (25) for different values of c (1, 2, 3, and 4 cm) (Fig. 5). These simulation graphs are compared with experiment graphs of the same variations of electric current I and voltage V;

A theory of corona discharge with multipoint–plane configuration has been discussed. The calculations of the

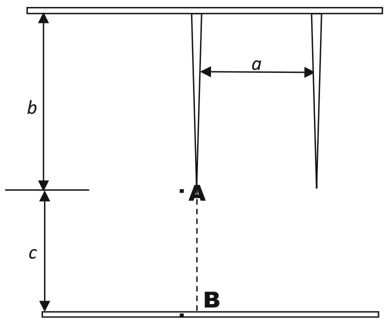

Fig. 4 Electric field calculation on the plane electrode (B) positioned at distance c from the point electrode (A)

electric field and saturated current generated from this configuration when input voltage V is applied have also been elaborated. The calculation of the total electric field resulting from $m \times n$ needle electrodes must be done using the concept of the electric field vector superposition. This research employs an arrangement of 8×4 needle electrodes with varied distances between the point-to-plane electrodes (c) at 1, 2, 3, and 4 cm.

The resulting graphs show that the simulation results are closer to the experiment results when the distance c is larger, especially for c at 3 cm and 4 cm. A narrower c causes an asymmetrical and inhomogeneous ion flow in which some areas are flooded with more ions than predicted. For a higher c, the symmetrical and homogeneous ion flow is closer to the experimental results. This causes an electric current reading that is closer to the expected value. Moreover, a narrower c does not allow the maximum electric field deviation angle from the induced point location to the perpendicular needle position, which may reach 67°, while greater c allows this to take place, hence, almost all ion flow that stems from the needle electrodes reaches all the designated points on the plane without the needles, and in turn, yields a greater electric field. Another influencing factor for the electric current reading is the shape of the needle with a sharpness no closer than 0°, which is the ideal condition for electric field calculation.

These statements can be explained as follows: Equation (14) shows the 3D vector of the ion current flow model that flows from the needle tip to the bottom plate with a parabolic shape as shown in Fig. 3. To simplify Eq. (14), we assume that the ion current flows symmetrically so that the flowing 3D vector will be changed to one direction in the upright axis (z-axis) because the ion current direction at the xy-plane will be a symmetrical circle; therefore, it will eliminate the others. Another assumption is that the ion current in the direction of the z-axis will be homogenously distributed and close to continuously flowing, so that the vector and discrete (summation) characteristics in Eq. (14) are changed to continuous (integration) and scalar characteristics (only in the direction of the z-axis) in Eq. (15), where Eq. (15) is part of Eq. (25). Therefore, the

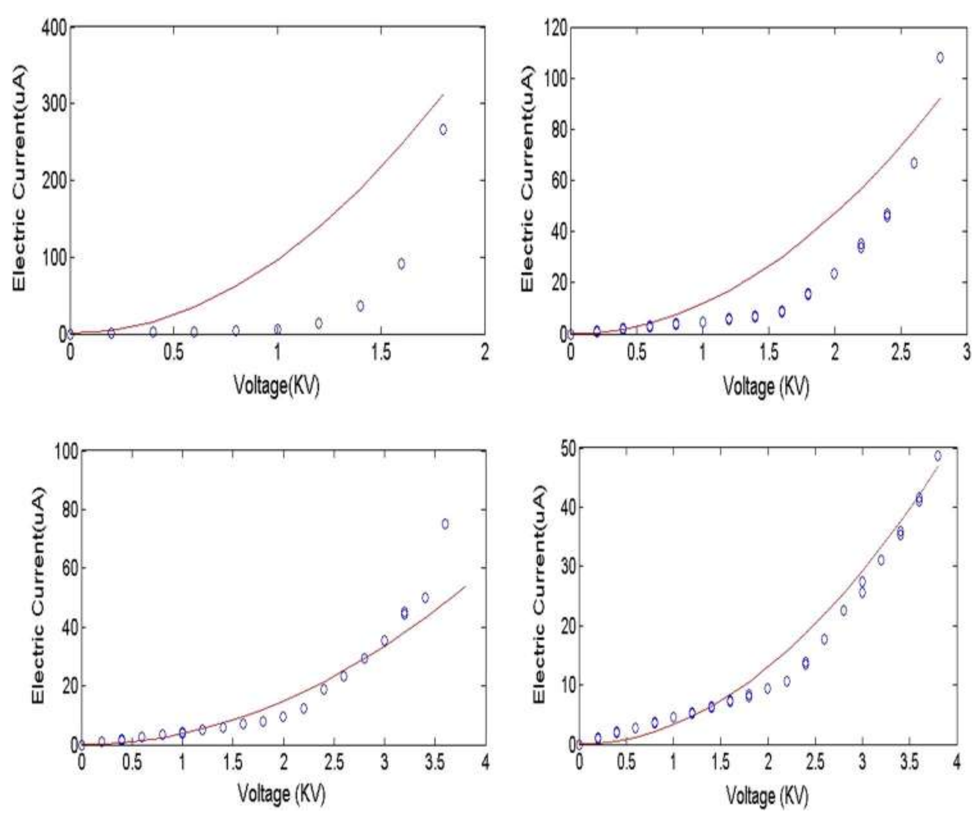

Fig. 5 Graphs of the relationship between the electric current I and voltage source V obtained from the $8 \times 4 = 32$ needle electrode configuration, limited to 67° for the maximum deviation angle for $a = 0.8068$ cm, $b = 0.018$ cm, and varied c at 1, 2, 3, and 4 cm. Blue circles indicate the experiment results. Red lines show simulation results from Eq. (25)

conditions of homogenous continuity and symmetry will be better for an increased distance from the multipoint–plane to the bottom plate surface, so that the mathematical simulation will match the results of the experiment at a greater value of c.

7. Conclusion

The current–voltage (I–V) characteristics that were produced by the corona discharge plasma generator for the multipoint–plane configuration in the air could demonstrate the performance of a device. The total electric field inducing these points could be calculated using the concept of the electric field vector superposition that stems from these needles. The total number of needles in this configuration is $8 \times 4 = 32$, and there is a variation of distance c, which is the distance between the point-to-plane electrodes. The comparison between the numerical simulation and experimental results indicated that the I–V characteristic curve is simulated better for longer distances between the point-to-plane electrodes, which is roughly longer than 3 cm; due to better symmetry and homogeneity of the ion current flows from the multipoint-plane to the plane configuration.

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