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Parametric Study and Optimization of Flow Characteristics of Wire-Nonparallel Plate-Type Electrostatic Air Accelerators

Wire and nonparallel plate electrode-type electrostatic air accelerators have attracted significant interest. The physical process involved in using accelerators is complicated. Moreover, mechanisms are unclear, especially for accelerators with double- and multi-wire electrodes. In this study, the two-dimensional (2D) model of a wire-nonparallel plate-type accelerator validated by experiments is established with a finite element method. Onset voltage, average current, and outlet average velocity are analyzed with respect to different parameters. Onset voltage is derived by the proposed quadratic regression extrapolation method. Moreover, current is affected by interference and discharge effects, while velocity is also influenced by the suction effect. For the single-wire electrode, high wind speed can be obtained by either increasing channel slope or placing the wire near the entry section. For the double-wire electrode, velocity can be further increased when one of the wires is placed near the inlet and the distance between the two wires is widened. Comparatively, the velocity of the three-wire electrode is higher with larger gaps between wires and stronger discharge effect. The highest velocity is obtained by the four-wire electrode. Comparisons indicate that higher velocity can be obtained with weaker interference effect, stronger suction effect, and intensified discharge effect. Optimum parameter combinations are considered by the Taguchi method. Consequently, velocity can be enhanced by more than 39% after optimization compared with the reference design. [DOI: 10.1115/1.4040016]

Keywords: corona discharge, accelerators, numerical analysis, optimization

1 Introduction

Ionic wind, also called corona wind, is a kind of particle perturbation phenomenon that occurs when charged particles move under an electric field after the corona is discharged into gaseous media. When high voltage is applied between electrodes in an uneven electric field, cold plasmas are generated by air ionization. The charged particles are then driven by electric force, thereby forming an air stream between the corona and the collector electrodes. Wind-driven devices based on the ionic wind principle, also called electrostatic air accelerators, have shown vast potential in the fields of flow control [1,2], electronic cooling [3,4], air drying [5,6], and enhanced combustion [7,8] due to advantages of low-energy consumption, use of nonmovable components, compact structure, and flexible design [9,10].

In extending the application of ionic wind devices, several electrode geometries (e.g., needle-to-mesh, pin-to-plate, wire-rod, and wire-to-plate) have been proposed to increase ionic wind velocity and conversion efficiency [11,12]. Qiu et al. [13] experimentally and theoretically analyzed the ionic wind velocity of serial-staged electrohydrodynamic (EHD) gas pumps using needle array-to-ring and needle array-to-mesh electrodes. Maximum average flow velocity was 7.39 m/s, volumetric flow rate was 140 L/min, and energy conversion efficiency was 0.8%. Zhao and Adamiak [14] numerically and experimentally investigated the EHD flow characteristics of pin-plate and pin-grid configurations. A numerical

algorithm based on finite element methods by using the commercial FLUENT software was adopted to solve problems on airflow. Komeili et al. [15] experimentally investigated the flow characteristics of a wire-to-rod-type EHD gas pump. Gas flow rate rose with the increase of EHD quantity and discharge current. A maximum gas flow rate of 40.1 L/min was generated by referring to optimal pipe diameter, grounding rod diameter, and gap-between-electrode values.

Among the abovementioned structures, the wire-to-plate electrode types (including wire-to-single-plate, wire-to-double-plates, and wire-to-channel structures) attracted significant attention [16,17]. Owsenek and Seyed-Yagoobi [18] theoretically and experimentally investigated heat transfer enhancement by focusing on wire-plate (single plate) corona discharge. Multiwire electrodes were suspended over a grounded heated plate, and the local heat transfer coefficients of the impingement surface were obtained then compared with other electrode geometries. Podlinski et al. [19] measured EHD flows with a wire discharge electrode and two collecting electrode plates in three-dimensional particle image velocimetry. Airflow was blown onto a reactor duct with an average velocity of 0.6 m/s. Field measurements on flow velocity illustrated a complex EHD-induced secondary flow in the non-thermal plasma reactor. Subsequently, a few other researchers have investigated the ionic wind phenomenon between wire electrodes and channels with different plates. Kasayapanand et al. numerically investigated the effect of EHD on natural convection in wavy channels [20], vertical channels [21], and open-square cavities [22]. The influence of several geometric parameters for flow and heat transfer enhancements was determined.

Unlike ionic wind devices with wire-to-plate electrodes, wire-nonparallel plate electrodes are unique because air can be

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gradually accelerated inside contraction channels [23,24]. Tsu-bone et al. [25] experimentally determined the flow characteristics of a wire-convergent-plate EHD gas pump in a rectangular flow channel with 3 deg slope. Gas velocity increased when additional voltage was applied. Consequently, a maximum average gas velocity of 1.9 m/s was achieved. Change et al. [26] experimentally investigated the mechanism of net flow direction of a wire-nonparallel plate-type EHD gas pump. Their results showed that gas could flow significantly depending on the location of the corona wire electrode relative to the grounded electrode. Kocik et al. [27] performed two-dimensional (2D) particle image velocimetry measurements to investigate the effects of electrode configuration and active electrode polarity on flow patterns inside a pump. Vortices were observed within the pump, and they negatively affected pumping capability. In addition to the abovementioned experimental studies, numerical studies have been performed to determine electric and flow profiles and verify physical laws. Ghazanchaei et al. [24] numerically predicted the flow characteristics of a wire-nonparallel plate-type EHD gas pump by using the finite element method. Velocity and pressure characteristics were compared and analyzed in detail after which the efficiency and the optimum geometric configuration were evaluated.

Despite the above efforts, the effects of diameter and location of wire electrodes have not been fully analyzed. Moreover, investigations on wire-nonparallel plate-type accelerators with double- and multiwire electrodes are still lacking. The flow characteristics of double- and multiwire electrode layouts may differ from those of single-wire electrode layouts; however, the interaction effects of multiple corona electrodes have not been specified. In addition, parametric optimizations using the multifactor design method for wire-nonparallel plate-type accelerators have yet to be conducted.

In this paper, 2D simulation models are adopted for wire-nonparallel plate-type electrostatic air accelerators with single-, double-, and multiwire electrode layouts. Onset voltage is measured using quadratic regression. The effects of various parameters, such as applied voltage, wire electrode diameter, flow channel slope, and wire electrode location, are investigated. These parameters are also optimized by the Taguchi method. The order of influence of the different factors is analyzed after which optimal cases are determined.

2 Physical and Mathematical Models

2.1 Physical Problem Description. Figure 1 shows the 2D diagram of a typical electrostatic air accelerator with wire and nonparallel plate electrodes. A convergent channel is formed in between two electrodes with nonparallel plates and wires. The wire electrodes are placed along the centerline of the channel. The wire electrodes are positioned at the four potential locations of L_a , L_b , L_c , and L_d . The distances from the inlet to the four locations are S_a , S_b , S_c , and S_d . Wire electrode radius and slope channel angle are designated as r_w and θ , respectively. Accelerator length is fixed at L (117 mm), while width is adjusted with respect to different slope angles. The default values of the above parameters are shown in Table 1. The wire electrodes are first applied with a positive electric potential (V), then the plates are prepared for

Fig. 1 2D model of an electrostatic air accelerator

grounding. Finally, air is suctioned into the channel from the inlet to produce airflow in the channel.

2.2 Governing Equations. The electric and flow characteristics of the accelerator are determined. The following equations are solved to obtain the values of electric potential (V), space charge density (q), and velocity (U):

Poisson's equation for electrostatics

$$\nabla^2 V = -\frac{q}{\epsilon_0} \quad (1)$$

Current density conservation equation

$$\nabla \cdot \mathbf{J} = 0 \quad (2)$$

Continuum equation

$$\nabla \cdot (\rho \mathbf{U}) = 0 \quad (3)$$

Momentum conservation equation

$$\mathbf{U} \cdot \nabla (\mathbf{U}) = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{U} + \frac{\mathbf{F}_e}{\rho} \quad (4)$$

Electric field ($\mathbf{E}$), current density ($\mathbf{J}$), and electric field force ($\mathbf{F}_e$) are expressed by

$$\mathbf{E} = -\nabla V \quad (5)$$

$$\mathbf{J} = \mu_e \mathbf{E} q \quad (6)$$

$$\mathbf{F}_e = q \mathbf{E} \quad (7)$$

2.3 Boundary Conditions. To solve Eqs. (1)–(7), the boundary conditions of electrostatic, space charge, and velocity fields are provided. For airflow, the inlet and outlet surfaces are imposed with pressure conditions. No-slip boundary conditions are also applied to the surfaces and walls of the electrodes. For electrostatics, a constant DC voltage is applied to the wire electrodes. Then, the plates are grounded. The boundaries other than surfaces of wire and plate electrode are assumed to have zero charge.

For space charge density, the space between the corona and the collector electrodes is divided into ionization and drift zones. Considering that the ionization zone of the corona discharge is very small relative to the transport zone, ionization is handled by a boundary condition for ion concentration. Therefore, an initial charge density q_0 is assumed and applied to the interface of the ionization zone and the drift area. The assumed space charge is used initially to solve Eqs. (1), (2), (5), and (6) and to obtain the current density of the collector electrode (J_p). Then, current density and charge density are matched following Peek's equation [28], as shown in the following equation:

$$q_0 = \frac{l_p J_p}{\pi \mu_e r_w f \left[30\delta + 0.9(\delta/r_w)^{1/2} \right]} \times 10^{-5} \quad (8)$$

where l_p , f , and δ are the length of collector electrode, roughness factor of electrode, and an environmental constant, respectively. The roughness factor is set to 0.95 in this study. The environmental constant is calculated by

$$\delta = \frac{T_0}{T} \times \frac{p}{p_0} \quad (9)$$

where T_0 and p_0 denote environmental temperature and pressure, respectively, while T and p denote accelerator temperature and pressure. Subsequently, the initially obtained J_p is added to Peek's

Table 1 Default values of the model

Applied voltage (V)/kV	Wire electrode diameter (r_w)/mm	Flow channel slope (θ)/deg	Distance from inlet			
			S_a /mm	S_b /mm	S_c /mm	S_d /mm
11	0.15	3	26.8	36.8	46.8	56.8

equation to obtain a new calculated value of q_0 . The calculation process is repeated until the relative deviation of q_0 between two successive levels is less than 5%. A zero diffusive charge flux condition is applied to the boundaries and surfaces of the wire electrodes. Table 2 shows a detailed description of the boundary conditions.

3 Solution Method and Model Verification

3.1 Solution Method. The simulation is operated with a finite element method (i.e., conducted in COMSOL MULTIPHYSICS). First, the electrostatic module is used to solve Poisson's equation. For charge transport, a coefficient partial differential equation module is adopted to solve the current density continuity equation. Then, the value of q_0 for the wire electrode surface is iterated until the calculated value is sufficiently near Peek's value. Finally, to obtain the flow characteristics, the continuum and momentum conservation equations are solved using the laminar flow module.

3.2 Grid Independence Analysis. The regular tetrahedral mesh is generated by COMSOL MULTIPHYSICS and prepared for simulation. Six grids with sizes of 6,520, 9,214, 14,227, 30,049, 68,300, and 106,073 are employed for the grid independence test. An evaluation index for average outlet velocity is considered. Figure 2 shows the average outlet velocities of meshes with different grid sizes. The number of meshes is increased by 50,000 from the fifth to the sixth grid. In addition, velocity enhancement ratio is less than 1%. Therefore, the fifth grid with 68,300 mesh size is selected for the simulation (i.e., a compromise between required accuracy and computation costs).

3.3 Simulation Method Verification. The model with default values is chosen to verify the simulation. Then, the simulation results for current density and average outlet velocity are compared with the experimental results of Tsubone et al. [25]. The geometric parameters of the accelerator in this study are consistent with those of the previous experiment. As shown in Figs. 3(a) and 3(b), the maximum deviations are 9.98% and 9.03% for current density and velocity, respectively. The deviations may be attributed to the simplification of the 2D models and the approximation of Peek's values; nonetheless, the relative deviations are both below 10%. From the validation, the calculation method in this study is considered to be reliable.

4 Results and Discussion

The verified numerical models are adopted to analyze the effects of several parameters, such as applied voltage, wire electrode diameter, wire electrode location, and channel slope. Accelerators with different wire electrode layouts are considered. Then,

Table 2 Boundary conditions of the model

Surface	Electrostatic field	Space charge field	Velocity field
Corona electrode	$V = V_0$	$q_c = q_0$	No slip
Collector electrode	$V = 0$	Zero flux	No slip
Inlet	Zero charge	Zero flux	Pressure
Outlet	Zero charge	Zero flux	Pressure
Others	Zero charge	Zero flux	No slip

Fig. 2 Average outlet velocity as a function of mesh quantity

(a)

(b)

Fig. 3 Verification of the simulation method: (a) verification of current density and (b) verification of average outlet velocity

the effects of parameters on onset voltage, voltage–current characteristics, and outlet velocity are investigated.

4.1 Current and Velocity of Wire Electrodes With Different Applied Voltages and Diameters. Wire electrodes with four different diameters (0.075, 0.1, 0.15, and 0.2 mm) are investigated alongside different voltages (9, 9.5, 10, 10.5, and 11 kV). A wire electrode is placed at L_d in the single-wire electrode layout. The effects of wire electrode diameter on voltage–current characteristics and average outlet velocity are shown in Figs. 4(a) and 4(b), respectively. Current and average outlet velocity are increased with the rise in applied voltage for each diameter, but they are decreased when diameter is increased at fixed applied voltage. This phenomenon can be illustrated by the formation mechanism of ionic wind. Figure 5 shows the potential, charge density, and velocity profile of a typical accelerator with 0.2 mm diameter wire electrode. According to the ionic wind principle, high potential can be produced in between the corona (wire) and the collector (plate) electrodes (Fig. 5(a)). Air molecules around the wire electrode surface are ionized; they also move to the collector electrode under Coulomb force (Fig. 5(b)). Moving ions continue to collide with neutral air molecules after which momentum is transferred to surrounding molecules. Then, airflow is formed (Fig. 5(c)). When applied voltage is increased, a few other air molecules are ionized from the surface of the wire electrode. Air molecules continuously collide with neutral molecules; thus, the number of charged particles also continues to increase. As more particles move into the

electric field, current and velocity are increased. The electric field also becomes nonuniform when difference in curvature radius is large between the thin wires of electrodes. A comparison of Fig. 6 with Fig. 5 shows that when more air molecules around the wire electrode are ionized, space charge density is higher. Therefore, both current and velocity can increase when wire electrode diameter is decreased.

4.2 Onset Voltage, Current, and Velocity of Wire Electrodes With Different Channel Slopes and Locations. Flow channel slope and wire electrode location are geometric parameters that may significantly affect the performance of accelerators. Apart from current and velocity, onset voltage is another critical characteristic value of corona discharge. The general I – V dependence for a steady corona discharge is given by Townsend's relation [29,30]

$$I = CV(V - V_s) \quad (10)$$

where C is a constant depending on geometric parameters. Onset voltage cannot be directly attained using the current simulation method because the ionization zone effect has been simplified as a boundary condition during calculation. However, the I – V characteristics can be obtained by simulation. The values of C and V_s are determined using quadratic regression extrapolation in which onset voltage is used as the intercept of the regression line. The simulation and fitting results at different channel slopes are shown in Fig. 7(a) and Table 3. The onset voltages (V_s) of the wire-to-plate-type accelerator can also be obtained by Peek's empirical formulation

$$V_s = m_v g_0 \delta^2 r_w \left(1 + \frac{0.301}{\sqrt{\delta r_w}} \right) \ln \left(\frac{2d}{r_w} \right) \quad (11)$$

where g_0 is the onset voltage gradient for the wire-to-plate structure and given by the value of 30 kV/cm, while factor m_v is set to 1 for smooth surfaces. Then, the calculated results from Peek's formulation in Eq. (11) are adopted to validate the quadratic regression extrapolation method. As shown in Table 3, the relative

Fig. 4 Current and velocity of wire electrodes with different diameters: (a) voltage–current characteristics at different diameters of wire electrodes and (b) average outlet velocity at different diameters of wire electrode

Fig. 5 Electric potential, space charge density, and velocity profile of an electrostatic air accelerator with single-wire electrode ($r_w = 0.2 \text{ mm}$, $V = 11 \text{ kV}$): (a) electric potential profile, (b) space charge density profile and electric field force vector distribution, and (c) velocity profile and stream line

deviations are all below 5%, which indicate that the method adopted in this study is reliable.

Figure 7(a) and Table 3 show that flow channel slope increases when onset voltage decreases and current increases. At a fixed accelerator length, the distance between wire and plate electrodes decreases when slope angle increases, thereby leading to relatively low onset voltage and relatively high current. Moreover, with increasing slopes, factor C in Eq. (11) also increases (i.e., see Table 3), which means that current range widens when unit voltage is enhanced. Therefore, current increases together with the increase in channel slope.

The onset voltage at different wire electrode locations is shown in Table 4, while the voltage–current characteristics are presented in Fig. 7(b). Onset voltage is relative low when the wire electrode is placed far from the inlet. Meanwhile, current increases when electrode location is changed from L_a to L_d . The difference can be attributed to the gap between wire and plate electrodes, which become relatively small when wires are placed far from the inlet, thereby resulting in low onset voltage and high current.

The velocity at the exit section is also affected by wire electrode location and channel slope. Figure 7(c) presents the outlet velocity for different slopes when the single-wire electrode is placed in four different locations ($V = 11$ kV). Regardless of the location of the wire electrode, velocity grows as slope angle increases; however, velocity does not vary regularly. Velocity is highest when the wire electrode is placed at L_a , while minimum velocity is obtained at L_b when slopes are 3 deg and 3.5 deg. Velocity decreases when the distance of the wire electrode from the inlet is increased or when the slope is 2.5 deg. In this study, when wire electrodes are placed in different locations, the velocity may be influenced by two competing effects: suction effect and discharge effect. When the wire electrode is placed near the entry section, an electric field is created close to the inlet. Then, the air near the inlet are easily suctioned, thereby leading to high velocity. This phenomenon is called the suction effect, and it is beneficial to velocity enhancement. By contrast, the gap between wire and plate electrodes becomes small when the wire electrode is placed far away from the inlet. Then, the discharge is strengthened and the velocity increased; this phenomenon is called discharge

Fig. 6 Electric potential, space charge density, and velocity profile of an electrostatic air accelerator with single-wire electrode ($r_w = 0.075$ mm, $V = 11$ kV): (a) electric potential profile, (b) space charge density profile and electric field force vector distribution, and (c) velocity profile and stream line

effect. The stronger the suction and discharge effects are, the more enhanced the velocity will be. However, the suction and discharge effects are opposing. In other words, considering the combined effects, velocity does not simply increase or decrease with the change in location of wire electrodes.

4.3 Current and Velocity of Double-Wire Electrodes at Different Locations. The characteristics of electrostatic air accelerators with double-wire electrodes may be affected by the

Fig. 7 Current and voltage of a single-wire electrode with different flow channel slopes at different locations: (a) voltage–current characteristics at different flow channel slopes, (b) voltage–current characteristics at different single-wire electrode locations, and (c) velocity at different single-wire electrode locations and flow channel slopes ($V = 11$ kV)

Table 3 Onset voltage at different flow channel slopes

Flow channel slope (θ)/deg	Expression of fitting curve $I = CV(V-V_s)$	Calculated onset voltage from Eq. (11) (V_s)/kV	Relative error
2.5	$I = 0.29507V(V-7.199)$	7.534	4.90%
3	$I = 0.32810V(V-7.093)$	7.423	4.44%
3.5	$I = 0.37565V(V-7.001)$	7.362	4.90%

Table 4 Onset voltage at different locations of the single-wire electrode

Wire electrode location	Expression of fitting curve $I = CV(V-V_s)$	Calculated onset voltage from Eq. (11) (V_s)/kV	Relative error
L_a (26.8)	$I = 0.23069V(V-7.334)$	7.677	4.47%
L_b (36.8)	$I = 0.25880V(V-7.247)$	7.597	4.6%
L_c (46.8)	$I = 0.29137V(V-7.168)$	7.512	4.58%
L_d (56.8)	$I = 0.32820V(V-7.093)$	7.423	4.44%

relative positions between two wires. Unlike in the case of the single-wire electrode, electric field is different in double-wire electrodes because of the interaction of two wires. In this study, the wire electrodes are placed in four possible locations (L_a , L_b , L_c , and L_d). Thereafter, six different double-wire electrode layouts are investigated. Figures 8(a) and 8(b) show the current-voltage characteristics and the average velocity of the double-wire electrodes positioned at different locations. As shown in Fig. 8(a), current is highest when the wire electrodes are placed at L_a-L_d and L_b-L_d , and discharge is weak when the electrodes are placed close to one another (i.e., L_a-L_b , L_b-L_c , and L_c-L_d). After considering the wind speed value in Fig. 8(b), the electrode layouts are divided into two groups: group 1 (L_a-L_c and L_a-L_d) and group 2 (L_a-L_b , L_b-L_c , L_b-L_d , and L_c-L_d). The velocity of group 1 is evidently larger than that of group 2. For group 2, the velocity is comparatively low because of the strong interference effect.

The interference effect can be derived from the velocity profile shown in Fig. 9. When wire electrodes are positioned with relatively small gaps, the velocity field of one of the wire electrodes may significantly affect the other. Apart from the interference effect, velocity is also influenced by the suction effect. The velocity at L_a-L_b is higher than that at L_b-L_d , although the interference effect at L_a-L_b is stronger. A reason may be that the wire electrode at L_a is near the inlet, which is beneficial for air suction. Owing to the relatively stronger suction effect, the velocity at L_a-L_b is higher than those at L_b-L_c and L_c-L_d . For group 1 (Fig. 8(b)), the velocity is high due to the strong suction effect and the weak interference effect. The velocity at L_a-L_c is higher than that at L_a-L_d with voltage ranging from 9.0 kV to 10.5 kV. With a weak interference effect, the suction effect dominates; thus, the velocity of the wire electrode placed near the inlet is higher than those placed farther away. The velocity at L_a-L_d is increased when the voltage is 11 kV. This occurrence can be attributed to the discharge effect dominating the layout when applied voltage is increased. Therefore, velocity can be affected by the three effects: interference, suction, and discharge. Comparisons show that velocity is higher when one of the wire electrodes is placed near the inlet (i.e., stronger suction effect) and when two wire electrodes are positioned farther away from one another (i.e., weaker interference effect). The stronger discharge effect also leads to a higher velocity.

The difference in discharge intensity (Fig. 8(a)) can be further explained by potential distribution (Fig. 10) and space charge density (Fig. 11). Subsequent comparisons indicate that the mutual interference between two neighboring wire electrodes are much stronger when wire electrodes are placed near one another. When two wire electrodes have very small gaps, the charged particles from the electrode surface may move to the discharge zone and collide with electrically opposing particles (Figs. 10(a) and 11(a)), thereby resulting in a neutralization effect. Then, the number of generated particles and space charge density are both decreased. Therefore, current can be deteriorated because of the

interference effect of wire electrodes. However, when two discharge zones are placed farther away from one another (i.e., see Fig. 10(b) versus Fig. 11(b)), the probability of collision between charged particles is lessened, thus leading to weaker mutual interference. When the two wire electrodes are placed at L_a and L_d , the interference effect is almost nonapparent (Figs. 10(c) and 11(c)) due to the relative large distance between the wire electrodes, which in turn results in the highest current. Hence, current is comparatively low between a pair of closely spaced electrodes.

Fig. 8 Current and velocity of a double-wire electrode at different locations: (a) voltage-current characteristics at different double-wire electrode locations and (b) average outlet velocity at different double-wire electrode locations

Fig. 9 Electric potential profile of a double-wire electrode at different locations: (a) velocity profile at L_a-L_b , (b) velocity profile at L_a-L_c , and (c) velocity profile at L_a-L_d

By comparing Figs. 8(a) and 8(b), a higher current does not necessarily result in higher velocity. The velocity at L_a-L_c is higher than that at L_b-L_d , but the current at L_b-L_d is higher than that at L_a-L_c . The inconsistency may be caused by different effects of current and velocity. The interference effect is similar for L_a-L_c and L_b-L_d . By contrast, the current at L_b-L_d is higher than that at L_a-L_c because of the stronger discharge effect. Velocity is also affected by the suction effect, which seems to dominate the channel when wire electrodes are placed at L_a-L_c . Hence, the inconsistency between current and velocity is evident because current is influenced by the interference and discharge effects while the velocity is affected by the above two effects together with the suction effect.

4.4 The Effect of Location of Multiwire Electrodes. For the electrostatic air accelerators with a multiwire electrode, five

different arrangements (i.e., four types of three-wire electrode layouts and one type of four-wire electrode layout) are investigated. Figure 12(a) shows the voltage-current characteristics of the multiwire electrodes at different locations. On the basis of current value, the three-wire electrode layouts are divided into two groups: group 1 ($L_a-L_c-L_d$ and $L_a-L_b-L_d$) and group 2 ($L_a-L_b-L_c$ and $L_b-L_c-L_d$). The currents of group 1 are much higher than those of group 2, and these currents are even higher compared with that of the four-electrode layout. Figure 12(b) shows the velocities of multiwire electrodes at different locations. The velocities of group 1 are higher than those of group 2 due to weaker interference effect given then larger distances in between electrodes. Moreover, the velocity is higher at $L_a-L_c-L_d$ than that at $L_a-L_b-L_d$. Thus, the interference effect is comparatively weak and a strong suction effect is guaranteed when wire electrodes are placed at L_a for both layouts. The discharge effect is stronger at $L_a-L_c-L_d$ than that at $L_a-L_b-L_d$, which in turn results in the highest velocity among the abovementioned three electrode layouts.

When multiwire electrode layout is applied, the currents of the four electrodes are lower than some of the three electrodes (i.e., $L_a-L_c-L_d$ and $L_a-L_b-L_d$). Nonetheless, the four-wire electrode layout still carries the highest velocity. As air flows through the channel, vortices appear around wire electrodes, as shown in Figs. 5(c), 6(c), and 9. The presence of vortices leads to energy loss, thereby reducing energy efficiency. The vortices around the intermediate wires of the electrodes are nonapparent because of the influence of edges of at least two-wire electrodes (Fig. 13). Thus, the interference effect can dissipate vortices around intermediate electrodes, thereby avoiding energy loss. This phenomenon also indicates that the interference effect may improve velocity in multiwire electrode layouts.

The characteristics of current are shown in Fig. 12(a), although they can be further illustrated by electric potential and space charge density profile (Figs. 14 and 15). Interference is evident when electrodes are placed near one another, a phenomenon which also reduces current. For group 1, currents differed only slightly when electrodes are placed at $L_a-L_c-L_d$ and $L_a-L_b-L_d$. Therefore, currents are not significantly affected by the electrodes at L_b and L_c , as the discharge of the intermediate electrode is affected by wire electrodes located at L_a and L_d . This effect can also be derived from the percentage of total current, as shown in Table 4. The current of an intermediate electrode is smaller than those of the two other electrodes in the three-wire layout. Electric

Fig. 10 Space charge density profile and electric field vector distribution of a double-wire electrode at different locations: (a) potential profile at L_a-L_b , (b) potential profile at L_a-L_c , and (c) potential profile at L_a-L_d

Fig. 11 Velocity profile and stream line of a double-wire electrode at different locations: (a) charge density profile at L_a-L_b , (b) charge density profile at L_a-L_c , and (c) charge density profile at L_a-L_d

Fig. 12 Current and velocity of a multi-wire electrode at different locations: (a) voltage–current characteristics at different multi-wire electrode locations and (b) average outlet velocity at different multi-wire electrode locations

particles emitted by the intermediate electrode are either absorbed by the surfaces of other electrodes or collide with electrically opposite particles until the generation and absorption rates of the particles are balanced. The intermediate electrode also needs to reach a discharge balance relative to the two other electrodes. In this case, particles collide further and the current of the intermediate electrode is at the lowest. Moreover, the currents of group 1 (i.e., three-wire electrode layout) are higher than those of the four-wire electrode layout. As shown in Tables 4 and 5, the percentages of the intermediate electrodes are the lowest among all four electrodes, which indicate that the two middle electrodes are affected by the edges of the two other electrodes. In fact, the current of the four-wire electrode is even lower than those of some three-electrode layouts.

5 Optimization of Electrostatic Air Accelerators

This study analyzes the effects of applied voltage, wire electrode diameter, flow channel slope, and wire electrode location on different electrode layouts. To determine the best parameter design and maximize the performance of electrostatic air accelerators, a multifactor design method is adopted. Then, the optimal conditions of single-, double-, and multiwire electrode models are established.

5.1 Multifactor Design Method. The method presented in this study is a design process called the Taguchi method. The

Fig. 13 Electric potential profile of a multi-wire electrode at different locations: (a) velocity profile at $L_a-L_b-L_c$, (b) velocity profile at $L_a-L_c-L_d$, and (c) velocity profile at $L_a-L_b-L_c-L_d$

Fig. 14 Space charge density profile and electric field vector distribution of a multi-wire electrode at different locations: (a) potential profile at $L_a-L_b-L_c$, (b) potential profile at $L_a-L_c-L_d$, and (c) potential profile at $L_a-L_b-L_c-L_d$

Taguchi method is a multifactor experimental design method based on orthogonal arrays [31,32]. Representative points are selected from full factorial experiments. Then, these points are distributed uniformly within the test range to represent an overall situation. The method is highly efficient when optimal combination levels are sought. In the method, a range (R) is used to evaluate the influence of each factor. With respect to the level change of a factor, the larger the range is, the higher the influence on test results will be. The ranks of influence of the factors are listed according to range values. Finally, the optimal case in this study is determined by a research index on outlet wind velocity.

5.2 Optimization of Electrostatic Air Accelerators With Different Wire Electrodes. From the simulation, four influential fabricating factors (i.e., wire electrode location, flow channel slope, wire electrode diameter, and applied voltage) are initially

Fig. 15 Velocity profile and stream line of a multi-wire electrode at different locations: (a) space charge profile at $L_a-L_b-L_c$, (b) space charge profile at $L_a-L_c-L_d$, and (c) space charge profile at $L_a-L_b-L_c-L_d$

selected for the accelerators with single-, double-, and three-wire electrodes. Considering that there is only one wire electrode layout for accelerator with four-wire layout, an analysis of the influence of wire electrode location is not necessitated; thus, only three factors are finally chosen. The factor levels in this study are shown in Table 6. Flow channel slope comprise three levels (2.5, 3, and 3.5); wire electrode diameter includes four levels (0.075, 0.1, 0.15, and 0.2 mm); and applied voltage varies from 9 kV to 11 kV

(i.e., gap is 1 kV). The locations of the single-, double-, three-, and four-wire electrodes comprise four levels (L_a , L_b , L_c , and L_d), six levels (L_a-L_b , L_a-L_c , L_a-L_d , L_b-L_c , L_b-L_d , and L_c-L_d), four levels ($L_a-L_b-L_c$, $L_a-L_b-L_d$, $L_a-L_c-L_d$, and $L_b-L_c-L_d$), and zero levels, respectively. The factors in this study are assumed to function independently.

Table 7 shows the optimization results of the different electrode layouts, including order of influence, optimum value, and maximum velocity. For the accelerator with three-wire electrodes, applied voltage is considered the most important influencing factor; meanwhile, flow channel slope and wire electrode location obtained similar ranges, although the values are generally considered as nonsignificant.

The voltage-current characteristics and velocity of the different electrode layouts are compared with default models. The default values of voltage, wire electrode diameter, and flow channel slope are shown in Table 1. The default locations of wire electrode are L_d , L_a-L_b , and $L_a-L_b-L_c$ for accelerator with single-, double-, and three-wire electrodes, respectively.

The comparison of the voltage-current characteristics between the default and optimization models is shown in Fig. 16. At the same voltage, the current increases significantly after optimization. The velocity enhancements of the different electrode layouts are shown in Fig. 17. After optimization, outlet average velocities are increased by 39%, 79%, 60%, and 46% for accelerators with single-, double-, three-, and four-wire electrodes, respectively. Thus, velocity is indeed enhanced, as shown by the results of the Taguchi method.

6 Conclusions

The influence of various design parameters on the electric and flow characteristics of electrostatic air accelerators with different wire electrodes is analyzed using a numerical methodology. Results show that average current and average outlet velocity

Table 5 Percentage of total current of the wire electrode

Percentage	$L_a-L_b-L_c$ /%	$L_a-L_b-L_d$ /%	$L_a-L_c-L_d$ /%	$L_b-L_c-L_d$ /%	$L_a-L_b-L_c-L_d$ /%
I_a	33.813	23.157	32.643	no	24.613
I_b	17.095	24.020	no	32.812	14.313
I_c	49.092	no	27.550	19.155	18.064
I_d	no	52.823	39.807	48.033	43.010

Table 6 Factor levels of the different wire electrodes

		Factors			
Electrode layout	Levels	A wire electrode location(distance from inlet)/mm	B flow channel slope (θ)/deg	C diameter of wire electrode (r_w)/mm	D applied voltage (V)/kV
Single wire	1	26.8 (L_a)	2.5	0.075	9
	2	36.8 (L_b)	3	0.1	10
	3	46.8 (L_c)	3.5	0.15	11
	4	56.8 (L_d)	3.5	0.2	11
Double wires	1	26.8/36.8 (L_a-L_b)	2.5	0.075	9
	2	26.8/46.8 (L_a-L_c)	3	0.15	10
	3	26.8/56.8 (L_a-L_d)	3.5	0.2	11
	4	36.8/46.8 (L_b-L_c)			
	5	36.8/56.8 (L_b-L_d)			
Three wires	6	46.8/56.8 (L_c-L_d)			
	1	26.8/36.8/46.8 ($L_a-L_b-L_c$)	2.5	0.075	9
	2	26.8/36.8/56.8 ($L_a-L_b-L_d$)	3	0.1	10
	3	26.8/46.8/56.8 ($L_a-L_c-L_d$)	3.5	0.15	11
Four wires	4	36.8/46.8/56.8 ($L_b-L_c-L_d$)	3.5	0.2	11
	1		2.5	0.075	9
	2		3	0.15	10
	3		3.5	0.2	11

Table 7 Optimization results of the different wire electrodes

Electrode layout	Order	Optimum values				
		A location of wire electrodes /mm	B flow channel slope(θ)/deg	C diameter of wire electrode (r_w)/mm	D applied voltage (V)/kV	Outlet average velocity /m·s ⁻¹
Single wire	C>D>B>A	26.8 (L_a)	3.5	0.075	11	0.87
Double wires	B>D>C>A	26.8/56.8 (L_a-L_d)	2.5	0.2	11	1.33
Three wires	D>C>B = A	36.8/46.8/56.8 ($L_b-L_c-L_d$)	3.5	0.075	11	1.46
Four wires	C>D>B		3.5	0.075	11	1.56

Fig. 16 Voltage-current characteristics after optimization

Fig. 17 Optimization results of different wire electrode layouts

increase when applied voltage is increased and when wire electrode diameter is decreased. Furthermore, velocity is enhanced when the slope angle is increased or when a wire electrode is placed near the entrance section. For the double-electrode layout, velocity is increased when one of the wire electrodes is placed near the inlet and when the distance between the two wire electrodes is far from one another. However, a layout with higher current does not necessarily lead to higher velocity because velocity is affected by interference, suction, discharge effects. Moreover, a suction effect occurs regardless of current values. For the three-wire electrodes, the current percentage of the intermediate wire is the lowest due to the interference of two surrounding electrodes. Velocity is highest for the relatively larger gaps in between wire

electrodes; the discharge effect in this layout is also relatively strong. Among all layouts, the four-wire electrode obtained the highest velocity, but current is lower than those of some three-electrode layouts. The inconsistency can be attributed to the interference effect in which energy loss is caused by vortices around intermediate wires. In this study, optimal parameter combinations are also determined using the Taguchi method to obtain the highest velocity. After optimization, outlet average velocities increased by 39%, 79%, 60%, and 46% for the accelerators with single-, double-, three-, and four-wire electrodes, respectively.

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Nomenclature

- E = electric field intensity, $V \cdot m^{-1}$
 f = roughness factor of electrodes
 F = electric force, N
 I = current, A
 J = current density, $A \cdot m^{-1}$
 L = location of the wire electrode (distance from inlet), mm
 P = electric power, W
 P = pressure, Pa
 Q = space charge density, $C \cdot m^{-3}$
 R = radius, mm
 S = distance from inlet, mm
 T = temperature, K
 U = velocity, m/s
 V = voltage, V

Greek Symbols

- Δ = environmental constant
 ε = dielectric constant, $F \cdot m^{-1}$
 θ = channel slope, deg
 μ = ionic mobility, $m^2 \cdot V^{-1} \cdot s^{-1}$
 ν = kinematic viscosity, $m^2 \cdot s^{-1}$
 ρ = density, $kg \cdot m^{-3}$

Subscripts

- avg = value of average
 E = value under electric field
EHD = value of EHD
max = value of maximum
w = value for wire electrode
0 = value of initial

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