

DEVICE ARRANGED TO PROVIDE AN AIR CURRENT AND RELATED METHOD

Field & Background

5 The present invention relates to a device arranged to provide an air current and method of using the device.

A solid state fan is an air propulsion device with no moving parts, and is often realised using an electro-hydrodynamic system that uses (negative) corona
10 discharge to ionize air molecules, and an electric field to then accelerate the ions. The principle behind a simple electro-hydrodynamic accelerator is as set out. Particularly, negative corona discharge is a well-studied topic in the field of electrostatics, in which a strong electric field is created around a discharge electrode of a small radius, resulting in emission of free electrons from the
15 surface of the discharge electrode. The free electrons then bombard air molecules, resulting in liberation of further electrons, causing a Townsend avalanche, i.e. a cloud of negatively charged air molecules to form an ionization region. The ionization region propagates due to an increasing amount of charge carriers (i.e. ions) in the air, and the ions are accelerated by the electric field
20 that created the ionization region, colliding with other air molecules in the vicinity to generate bulk air flow away from the discharge electrode to form a drift region.

As explained, much research have been carried out to date on investigating
25 corona discharge and the acceleration of ionized air molecules in the drift region. Conventionally, setups configured for corona discharge are typically arranged with a sharp, tapered needle as a discharge electrode and a coaxially mounted ring as a counter electrode, separated by a small gap. However, many existing setups use a single set of discharge electrodes, with a single set of
30 counter electrodes, causing a maximum flow rate of air current generated to be limited by the breakdown voltage of air, beyond which arcing is inevitable. Some setups may use multiple sets of discharge electrodes coupled with an equal number of counter electrodes, which beneficially yields an increase in maximum flow rate, but still suffer from the same drawbacks. All present setups also make
35 use of a static electric field for accelerating the ions. Hence, the performance of

conventional setups (in terms of attaining usable flow rates) rely substantially on using high discharge voltages (i.e. voltages exceeding 10,000 V), which undesirably pose a significant safety hazard to operators of the setups, and also necessitate use of large cumbersome power supplies that are impractical for portability applications.

One object of the present invention is therefore to address at least one of the problems of the prior art and/or to provide a choice that is useful in the art.

10 **Summary**

According to a 1st aspect of the invention, there is provided a device arranged to provide an air current, comprising an ion generating device configured to generate an electrostatic field to ionize air molecules; at least one power source; and a plurality of electrodes electrically coupled to the at least one power source configured to cause the electrodes to generate respective oscillating electric fields to progressively increase a speed of the ionized air molecules to generate the air current.

Advantageously, the device uses the oscillating electric fields of relatively low voltage amplitude to accelerate the ions, and is able to attain a satisfactory flow rate without use of extremely high voltages. Further, an accelerating voltage used for the device may be significantly smaller to a discharge voltage (applied to the ion generating device), thus reducing a size and complexity of the power source required, thereby making it possible to integrate the device into a portable package.

Preferably, the electrodes may include being sequentially arranged as respective stages, which are classified into odd and even stages.

30 Preferably, each stage may include a pair of electrodes in opposing arrangement, and sequentially arranged includes being serially arranged.

Preferably, a number of the stages may include ten stages.

Preferably, the ion generating device may include a corona discharge ionization device or a RF plasma generator.

5 Preferably, the device may further include a driving electronics device electrically coupled to the at least one power source and electrodes, wherein the driving electronics device is configured to transmit first and second signals to the electrodes to cause the electrodes to generate the respective oscillating electric fields.

10 Preferably, the driving electronics may include an accelerating voltage power supply arranged to output an accelerating voltage and, wherein the first and second signals respectively include the accelerating voltage and a ground potential.

15 Preferably, the accelerating voltage may be configured to be between 300 V to 500 V.

20 Preferably, the driving electronics device may be configured to switchably transmit the first and second signals to between the odd and even stages respectively at a predetermined frequency.

Preferably, the predetermined frequency may include a frequency of 167 Hz.

25 Preferably, the stages in the serial arrangement may be arranged into concentric rings.

Preferably, each stage may be spaced from another adjacent stage by a predetermined distance.

30 Preferably, the predetermined distance may range between 5.00 mm to 6.12 mm.

Preferably, the ion generating device may include at least one discharge electrode configured to generate the electrostatic field.

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Preferably, the discharge electrode may be biased at a voltage of -4500 V. It is to be appreciated that the biasing voltage is also configurable to be significantly lower, depending on a specific design of the discharge electrode adopted.

5 According to a 2nd aspect of the invention, there is provided a method of providing an air current using a device which includes an ion generating device, at least one power source and a plurality of electrodes electrically coupled to the at least one power source, the method comprises generating an electrostatic field using the ion generating device to ionize air molecules; and configuring the
10 at least one power source to cause the electrodes to generate respective oscillating electric fields to progressively increase a speed of the ionized air molecules to generate the air current.

It should be apparent that features relating to one aspect of the invention may
15 also be applicable to the other aspects of the invention.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

20 **Brief Description of the Drawings**

Embodiments of the invention are disclosed hereinafter with reference to the accompanying drawings, in which:

FIG. 1 includes FIGs. 1a to 1c, which illustrate a proposed method of accelerating negatively-charged air molecules using an oscillating electric field;

25 FIG. 2 is a table depicting electrode distances (measured in millimetres), x_n , between nth and (n+1)th electrode;

FIG. 3 is a block diagram of a device arranged to provide an air current using the proposed principle of FIG. 1, according to an embodiment;

FIG. 4 is a circuit diagram of driving electronics for controlling counter electrodes
30 of said device of FIG. 3;

FIG. 5 includes FIGs. 5a to 5c, which show respective photographs of various components of a prototype of the device of FIG. 3;

FIG. 6 is a graph depicting performance results of the prototype, if a single-stage counter electrode is used;

FIG. 7 is a graph depicting performance results of the prototype, if a 2-stage counter electrode is used;

FIG. 8 is a graph depicting performance results of the prototype, if a 3-stage counter electrode is used;

5 FIG. 9 is a graph depicting performance results of the prototype, if a 4-stage counter electrode is used;

FIG. 10 is a graph depicting performance results of the different variants of the prototype of FIGs. 6 to 9;

10 FIG. 11 is a graph depicting performance results of the prototype, if a 10-stage counter electrode is used;

FIG. 12 shows a method for generating air current using a static electric field to accelerate ions generated in a corona discharge, according to prior art; and

FIG. 13 includes FIGs. 13a to 13c, which show the proposed method used by the device of FIG. 3 to generate air current using an oscillating electric field to
15 accelerate ions generated in a corona discharge.

Detailed Description of Preferred Embodiments

Referring to FIG. 3, a block diagram of a device 300 arranged to provide an air current is depicted, according to an embodiment. The device 300 includes an
20 ion generating device 302 configured to generate an electrostatic field to ionize air molecules; at least one (voltage) power source 304; and a plurality of electrodes 306 electrically coupled to the power source 304 configured to cause the electrodes 306 to generate respective oscillating electric fields to progressively increase a speed of the ionized air molecules, or ions (i.e. these
25 two terms will be used interchangeably hereinafter) to generate the air current. Hence, collectively, it is also to be appreciated that the electrodes 306 may be known as an accelerating electrode array. So, the device 300 is an electro-hydrodynamic accelerator, or simply known as a solid-state fan. The ion generating device 302 is realised using at least one discharge electrode, but in
30 this case, multiple discharge electrodes are used, as depicted in FIG. 3. So hereinafter, the discharge electrodes are used to refer to the ion generating device 302. The discharge electrodes 302 are electrically coupled to the power source 304, but if necessary, a separate dedicated power source for the discharge electrodes 302 may also be used. The plurality of electrodes 306 (i.e.
35 alternatively termed as counter electrodes, and referred to as such hereinafter)

arranged to generate respective oscillating electric fields are electrically coupled to an associated driving electronics device 308, which are in turn electrically coupled to a controller 310. The controller 310 instructs the driving electronics device 308 to transmit appropriate waveform signals to the counter electrodes
5 306 in order to generate the oscillating electric fields, and this will be elaborated further below.

In this instance, each counter electrode 306 is arranged to have a ring shape, and the respective counter electrodes 306 are sequentially and serially arranged
10 within and along an instrument cylindrical tube (to be explained further below) such that the centre point of each counter electrode 306 lies on the longitudinal axis of the tube. In this arrangement, the surfaces of the counter electrodes 306 conform to the surface of the tube, and each counter electrode 306 is arranged to be spaced from immediate neighbouring counter electrodes 306 by a
15 predetermined distance (i.e. see FIG. 2). The electrical connection of the counter electrodes 306 to the driving electronics device 308 is configured such that odd pairs of counter electrodes 306 are electrically coupled to a first set of wires of the driving electronics device 308, while even pairs of counter electrodes 306 are electrically coupled to a second set of wires of the driving
20 electronics device 308. In operation, the driving electronics device 308 transmits a first voltage signal to the first set of wires, and a second voltage signal to the second set of wires, and then alternate that signal transmission based on a driving frequency as configured to the driving electronics device 308, so that the driving electronics device 308 then switch to transmit the second
25 voltage signal to the first set of wires, and the first voltage signal to the second set of wires. In this case, the first and second voltage signals are respectively an accelerating voltage (of the driving electronics device 308) and a ground potential. It is to be appreciated that this switchable transmission of the different voltages to between the first and second set of wires repeats at a rate based on
30 the driving frequency. So, the oscillating electric fields are generated at a frequency corresponding to the driving frequency. The driving frequency is configured through the controller 310. Accordingly, by way of configuring the counter electrodes device 306 with alternating voltages as set out above, respective oscillating electric fields are consequently set up within the tube by
35 the counter electrodes 306 to accelerate the ions. It is to be appreciated that

the accelerating voltage is configured to be between 300 V to 500 V (to be clarified in later paragraphs below).

More specifically, the proposed device 300 is configured to use the oscillating electric fields of relatively low voltage amplitude to accelerate the ions. Advantageously, the device 300 is able to attain a comparable flow rate without use of extremely high voltages. As explained, the discharge electrode 302 is used to ionize air molecules, and the ions are subsequently accelerated by oscillating electric fields generated by the counter electrodes 306 applied with voltages of alternating polarities at a time-varying potential. Consequently, an accelerating voltage used for the device 300 may be significantly smaller than a discharge voltage (applied to the ion generating device 302), thus reducing a size and complexity of the power source 304 required, thereby making it practical to integrate the entire device 300 into a convenient, portable package.

For purpose of performance evaluations of the device 300, a hot-wire anemometer probe 312 coupled to an anemometer 314 (e.g. CEM DT-8880) is arranged at a fan exit of the tube arranged with the counter electrodes 306 to take necessary repeated measurement data relating to volumetric flow rate of the air current generated. The fan exit here refers to a second end of the tube opposite to a first end of the tube where the ions are introduced into the tube. As will be appreciated, a last stage of the accelerating electrode array may not be positioned at the fan exit, since a number of stages used may be less than the full length of the tube. The anemometer 314 wired/wirelessly communicates with a computing device 316 (e.g. computer/laptop) for transmitting measurement data taken thereto for analysis. It is to be appreciated that the anemometer probe 312, anemometer 314 and computing device 316 are not part of the device 300. Further, an ozone concentration monitor (not shown) may also be deployed in the vicinity of the device 300, and is deployed solely as a safety precaution to ensure that the ozone by-product generated by the device does not reach unsafe levels.

- ***Design Considerations***

In formulating a design for the proposed device 300, various relevant parameters were first investigated to determine relationships between the parameters and

any observed change in volumetric flow rate of air current that may be generated by the device 300. Specifically, the following parameters were taken into account for this investigation:

- 5 1. Discharge voltage (v_0);
2. Electrode geometry (of the counter electrodes 306);
 - Ring or mesh type;
 - Thickness of each counter electrode 306;
 - Distances between neighbouring counter electrodes 306;
- 10 3. Number of stages (n) of the counter electrodes 306;
4. Accelerating voltage (ΔV_{stage}); and
5. Driving frequency (f).

It is to be appreciated that the discharge voltage sets up an electrostatic field that ionizes air molecules and provides an initial accelerating force to move the ions. Increasing the discharge voltage increases an initial flow rate of the air current generated by the device 300, but however, using a high discharge voltage may cause the device 300 to be vulnerable to arcing, and hence undesirably necessitates a large, impractical power supply to be used.

20 Electrode geometry of the counter electrodes 306 affects both a shape and a magnitude of the oscillating electric field generated. For example, a mesh electrode design provides a field shape offering better horizontal acceleration (to the ions), since field lines generated are perpendicular to the surface of a conductor (e.g. copper). But however, the perpendicular field lines pose a significant obstruction to generated air current, resulting in significant performance losses when a multi-stage configuration is used for the accelerating electrode array. On the other hand, while a ring electrode design may provide less horizontal acceleration to the ions, but the ring electrode design beneficially
30 does not obstruct generated air current and thus do not cause performance losses in multi-stage designs for the accelerating electrode array. Specifically, it is to be appreciated that for this embodiment, a ring electrode design is adopted for the device 300, but however does not preclude other electrode geometry designs from being used in other embodiments, depending on suitability.

A thickness of a counter electrode 306 affects an amount of volume, which is at a certain potential. The “volume” in the preceding statement refers to a spatial, cylindrical volume enclosed within the surface of the cylinder. By extension, the air occupying the volume is at a certain specific potential as well, and thus gain
5 energy as the air travels between the various volumes arranged at different oscillating potentials. Briefly, it is to be appreciated that a surface coplanar to and within a charged ring is at a same potential as the charged ring itself. Consequently, thicker counter electrodes 306 permit phase-shifted ions to face a lesser penalty for being out of phase with reference to the oscillating electric
10 fields, hence improving the performance of air current generation by the device 300.

Respective spacing between neighbouring counter electrodes 306 is determined by equation (7) below, with an initial gap set to be x_0 to simplify a process for
15 fabricating the counter electrodes 306. The counter electrodes 306 are fabricated by pasting electrode strips manually onto a tube to form the counter electrodes 306, in an effort to reduce costs. In order to maintain integrity of experimental data obtained, the scale of electrode dimensions and separation distances (i.e. smaller than 3 mm) is to be arranged such that small errors made
20 in cutting/affixing the electrode strips (i.e. smaller than 0.5 mm) do not have a significant impact on the experimental data generated.

Further, as a number of stages (of counter electrodes 306) to be used in the accelerating electrode array increases, an amount of energy imparted to each
25 ionized air molecule increases correspondingly as well. Hereafter for simplicity, whenever the term “stage” is used together with in the context of the accelerating electrode array, it is to be understood that the stage refers to a stage of counter electrodes 306 arranged in the accelerating electrode array.

30 Also, increasing an accelerating voltage yields an increased amount of energy imparted to each ionized air molecule per stage utilised (for the accelerating electrode array), hence further improving the air current generation performance of the device 300.

As mentioned, the oscillating electric fields generated by the counter electrodes 306 are a result of alternately applying the accelerating voltage and ground potentials respectively to the odd and even sets of counter electrodes 306 at an intended driving frequency controlled by the driving electronics device 308. For the investigation, the driving frequency is varied at different values to find an optimum value, so as to ascertain whether the device 300 may then consequently yield comparable/improved performances for air current generation compared to conventional devices which conversely use an electrostatic field to achieve the same functionality.

• **Theoretical Analysis**

The purpose of this analysis is to find optimum conditions that would enable a highest flow rate of air current to be generated towards at a last stage of the accelerating electrode array. To achieve this, conditions necessary to maximize a velocity of the fastest particle (i.e. an ion), which is defined as a particle that arrives from one stage to a next stage (of the accelerating electrode array) at an exact moment the said next stage switches from a voltage of +300 V to 0 V (i.e. see FIGs. 1a-1c), need to be determined. This is to ensure that the particle is continually travelling up a potential gradient as set up within the accelerating electrode array, and therefore being accelerated continuously for generating the air current. The particle gains an energy of magnitude $K=q\Delta V_{stage}$ for passing through each stage of the accelerating electrode array, where q denotes a charge of the particle and ΔV_{stage} denotes an accelerating voltage configured between two adjacent stages. A difference in kinetic energy between the stages may be expressed as $q\Delta V_{stage}$, assuming there is negligible energy loss.

Additionally, since the accelerating electrode array is arranged in the form of concentric rings (i.e. based on the ring electrode design), effects of the particles laterally displaced away from the longitudinal axis of the tube (which comprises the respective stages of the accelerating electrode array) nullify one another, beneficially allowing analysis of the device 300 to be considered in only one dimension, simplifying matters.

Accordingly,

$$K_{n+1} = K_n + q\Delta V_{stage} \quad (1)$$

$$\frac{1}{2}mv_{n+1}^2 = \frac{1}{2}mv_n^2 + q\Delta V_{stage}, \quad (2)$$

wherein K_n denotes the kinetic energy of the (accelerated) particle at stage n , q is a charge of the particle, m is the mass of the particle, and v_n is a velocity of the fastest particle after passing through stage n . Re-arranging equation (2) gives:

$$v_{n+1}^2 - v_n^2 = \frac{2q}{m}\Delta V_{stage} \quad (3)$$

It is to be appreciated that ΔV_{stage} is assumed to be constant between the different stages, as set out in equation (4) below:

$$\begin{aligned} v_2 &= \sqrt{v_1^2 + \frac{2q}{m}\Delta V_{stage}} \\ v_3 &= \sqrt{v_2^2 + \frac{2q}{m}\Delta V_{stage}} \\ &= \sqrt{v_1^2 + 2\frac{2q}{m}\Delta V_{stage}} \end{aligned} \quad (4)$$

This consequently allows equation (3) to be generalised for n to provide:

$$v_n = \sqrt{v_1^2 + (n-1)\frac{2q}{m}\Delta V_{stage}} \quad (5)$$

An electric field generated between two successive stages of the accelerating electrode array is modelled as a uniform electric field, thereby providing a constant acceleration between the two stages. This then gives:

$$F = ma = qE = \frac{qV}{d}$$

$$\therefore a = \frac{qV}{md} \quad (6)$$

Next, let x_n denotes a distance between the n th and $(n+1)$ th counter electrodes 306. Since an acceleration of the particle is constant, this gives:

$$x_n = v_{avg} t = \frac{v_n + v_{n+1}}{2} t \quad (7)$$

A time taken by the particle to travel between stages n and $n + 1$ is then simply:

$$t = \frac{x_n}{\frac{v_n + v_{n+1}}{2}} = \frac{2x_n}{v_n + v_{n+1}} \quad (8)$$

For convenience, the following equation is also defined:

$$w = \frac{2q}{m} \Delta V_{stage} \quad (9)$$

wherein $\frac{q}{m} = \rho$, and so substituting equations (5) and (9) into equation (8) gives:

$$t = \frac{2x_n}{\sqrt{v_1^2 + (n-1)w} + \sqrt{v_1^2 + nw}} \quad (10)$$

To find an optimal driving frequency at which to switch electrical polarities applied to the odd and even stages of the accelerating electrode array, a constant distance of $x_0 = 5$ mm (i.e. a distance separating the discharge electrode 302 and a first stage of the accelerating electrode array, wherein the first stage is arranged immediately adjacent to the discharge electrode 302) is selected in order to derive $\frac{1}{t}$, which is the required optimal driving frequency.

Meanwhile, a value of w is determined experimentally by measuring a velocity of the air current after immediately passing through the first stage of the accelerating electrode array. Before air molecules are ionised by the discharge electrode 302, the air molecules are assumed to be stationary with zero kinetic energy, in this instance. Hence, when the ionized air molecules passes through the first counter electrode 306, kinetic energy of magnitude $K=q\Delta V_{stage}$ is gained by the ionized air molecules, and

$$\frac{1}{2}mv_1^2 = q\Delta V_0 \quad (11)$$

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wherein V_0 is a potential difference between the discharge electrode 302 and the first stage. So re-arranging equation (11) then gives:

$$w = \frac{v_1^2}{\Delta V_0 \Delta V_{stage}} \quad (12)$$

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From an average velocity, v_{avg} , of the particle as measured after passing through the first stage, the value of w is determined using equation (12), since $v_1 \approx v_{avg}$ when there is only one stage, thereby allowing t to be determined from equation (10) and x_n for all subsequent n from equation (7). Thus, given ΔV_0 , ΔV_{stage} , v_1 and x_1 , the optimal driving frequency to be adopted for alternating the voltages of the odd and even stages of the accelerating electrode array between the accelerating voltage and ground potential, and an optimal distance between each pair of stages of the accelerating electrode array are determinable.

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It is to be appreciated that from preliminary readings as provided by the analysis, the following values are obtained: $v_1 = 0.87$ m/s when $\Delta V_0 = 4650$ V, $\Delta V_{stage} = 300$ V and $x_1 = 5$ mm. So substituting the above mentioned numerical values of the various parameters into equation (12), the corresponding value of w is computed to be 0.0488 m²/s², and from equation (8), the optimal driving period t is calculated to be 0.00600 seconds. Hence, the optimal driving frequency is about 167 Hz. Further, using equations (5) and (7), respective optimal distances between neighbouring stages of the accelerating electrode array are determined and tabulated in a table 200 shown in FIG. 2.

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- **Methodology**

A systematic investigation into the various experimental parameters for designing the device 300 was performed, with an initial intention to identify an ideal electrode design (for the counter electrodes 306) so as to subsequently enable (larger and more elaborate) prototypes of the device 300 to be constructed. Testing of various electrode designs was carried out by locating stages of the accelerating electrode array at a predetermined distance from the discharge electrodes 302, in order to allow relative performance to be assessed. A dependent variable of interest, acting as an indicator of performance, is defined to be an observed flow velocity of the air current generated as measured by the anemometer probe 312. In this case, the anemometer probe 312 is positioned at about 10 mm from the last stage of the accelerating electrode array for taking the measurements. To clarify, the last stage is arranged diametrically opposite to the first stage of the accelerating electrode array.

The investigations start off by first using a single stage setup for the accelerating electrode array to determine performance obtained from different electrode designs. Thereafter, the electrode design determined to have good performance and proved to be most effective in the conventional single stage setup was adopted into a two-stage setup. Specifically, the two-stage setup is first tested with a standard, non-oscillating field, and then with an oscillating electric field of varying frequencies. Wind velocity readings of the air current generated are measured by the anemometer probe 312, and readings are taken continuously for about two minutes from the time the accelerating electrode array are initially powered on. The flow velocity of the air current generated by the device 300 is allowed to stabilise during the first thirty seconds, and so any associated data collected over that thirty seconds period are discarded. The mean and standard deviation of the remaining data collected between after the thirty seconds period and until end of the two minutes are then calculated, and compared to quantify improvements (if any) of utilising an oscillating electric field for the device 300 on the observed flow velocity of the air current, compared to a conventional device that uses a non-oscillating electric field for the same functionality. It is to be appreciated that empirical confirmation of the proposed method (of FIG. 1) that using an oscillating electric field for generating air current is advantageous over using a non-oscillating electric field is indicated by presence of a peak in

wind velocity at a specific frequency which is predicted in the “*Theoretical Analysis*” section above, as well as an overall increase in flow velocity of the air current compared to situations where a non-oscillating electric field is used instead.

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Thereafter, additional stages are then progressively and incrementally added to the accelerating electrode array, with flow velocity measurements taken at varying frequencies for each additional stage added. The measurements taken are processed in the same manner set out previously above, and compared.

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Another prototype of the device 300 with ten stages in the accelerating electrode array is also implemented. A range of frequencies (e.g. 50 Hz to 550 Hz) in the vicinity of the optimal driving frequency are tested, and flow velocities of the air current generated subsequently are compared against corresponding results where the accelerating electrode array are arranged with fewer stages to justify

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any claims of improvement. The voltages ΔV_0 and ΔV_{stage} , which were configured to be constant in the foregoing trials explained, are however increased in a final set of trial to demonstrate potential improvements the device 300 is capable of performing.

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• **Experimental Setup**

The design of an experimental setup for the device 300 requires a multi-faceted approach, particularly due to difficulties in switching the moderately high accelerating voltage at variable frequencies. Referring to FIG. 3, the driving electronics device 308 is custom designed and built to provide necessary voltages to facilitate the setup to generate oscillating electric fields. The driving electronics device 308 is designed with a modular architecture in mind, so that components may be replaced easily to enable different evaluation tests to be performed on the device 300, and also significant effort was taken to ensure that all high voltage components of the driving electronics device 308 and power source 304 are electrically isolated from one another and the electrical mains. It is to be appreciated that the electrical mains (i.e. running at 230 V and 50 Hz) is not part of the driving electronics 308 or the power source 304.

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FIG. 4 is a circuit diagram 400 of the driving electronics device 308 for controlling the accelerating electrode array of the device 300. Specifically, the

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controller 310 is configured to perform waveform generation, and in this case, is realised using a microcontroller (e.g. an ATmega32u4) to drive the gates of several logic devices 402 (of the driving electronics device 308), which ground the counter electrodes 306, but otherwise connected by respective pull-up resistors 404 to an accelerating voltage power supply 406 of the driving electronics device 308. An example of the logic devices 402 that may be used is ST-MicroelectronicsTM STF3NK100Z N-channel MOSFETs. FIG. 5a shows a photo 500 of the driving electronics device 308 used in the experimental setup. The accelerating voltage power supply 406 is adapted from a CCFL inverter salvaged from an HP ScanJet printer unit, and outputs a variable voltage range from 300 V to 500 V under load, during operation of the accelerating electrode array. The accelerating voltage power supply 406 provides the accelerating voltage, the purpose of which has already been afore explained. Separately, the power source 304 (as shown in a photo 510 of FIG. 5b) is used to facilitate generation of an electrostatic field by the discharge electrode 302 for producing the negative corona. Further, an ammeter (not shown) is electrically coupled between the discharge electrode 302 and the power source 304 to monitor for abnormal discharge currents, as a safety precaution. It is to be appreciated that a linear power supply 408 (of the driving electronics device 308) provides a voltage to the CCFL inverter used for accelerating voltage generation. The voltage provided by the linear power supply 408 varies with a driving frequency, and so use of a variable voltage power supply is necessary. In other embodiments, the variable voltage power supply may alternatively be replaced by a switch mode power supply arranged with additional linear regulation.

Mounts for attaching the respective stages to collectively form the accelerating electrode array are adapted (for example) from lab vises, fibre-enhanced materials, and used other steel parts for structural support. The mounts are arranged along the length of an extruded aluminium track (not shown), which allows for smooth and accurate positioning of the counter electrodes 306, and also permit easy, modular replacement of various components in the setup, thereby making it convenient to evaluate various different parameters to greater detail than otherwise possible. Each stage of the accelerating electrode array is arranged to be able to fit within an instrument tube (as already explained above), in which the anemometer probe 312 may be mounted to. Other suitable

cylindrical tubes may also be used in place of the instrument tube, as will be appreciated. So the stages are first mounted on the extruded aluminium track after which the track is then installed in the instrument tube to complete assembly of the accelerating electrode array. When installed in the tube, the
5 extruded aluminium track runs parallel to the longitudinal axis of the tube. As seen from FIG. 4, the odd and even stages of the accelerating electrode array are coupled to the driving electronics device 308 respectively via the first and second set of wires.

10 • **Results and Analysis**

Despite the mesh electrode design offering better performance in a trial of a single-stage prototype (of the device 300), obstruction imposed by the perpendicular field lines of electric fields generated by counter electrodes with the mesh-shape on the air current becomes a significant factor when extending
15 to a multiple stage design for the accelerating electrode array. Hence, the ring electrode design was selected to minimise a number of uncontrolled variables and to enable effects of additional stages (of the accelerating electrode array) on flow velocity of the air current to be more apparent and reliable. Indeed, the ring electrode design was found to be more favourable, due to better performance in
20 preliminary testing. Further, using the ring electrode design also resulted in lesser difficulties encountered, in terms of not requiring the counter electrodes 306 to be fabricated precisely, and thus so the counter electrodes 306 exhibited less variability in dimensions that may arise from any slight defects of the fabrication.

25 The single-stage prototype was tested at different driving frequencies in a predetermined range, and flow velocity readings of air current generated by the single-stage prototype are obtained and plotted against the respective driving frequencies, as shown in a linear regression graph 600 of FIG. 6. It is to be
30 noted that readings obtained in respect of the single-stage prototype are used as a baseline reference for comparison with other multi-stage prototypes. The linear regression pattern overlaid on the graph 600 suggests that there is little, if any, change in flow velocity arising from an increase in driving frequency used. This coincides with the theoretical explanation, which shows that there are no
35 expected effects on the flow velocity since no oscillating electric fields are

generated to further oscillate the ions. It is to be appreciated that readings are taken of the single-stage prototype operating with a time-constant non-oscillating electric field, and the flow velocity v_0 was found to be about 0.82 m/s.

5 Next, readings obtained from a 2-stage prototype (of the device 300) are plotted as depicted on a graph 700 of FIG. 7, which does not appear to have a linear pattern, unlike the readings obtained from the single-stage prototype. Hence, in this case, a cubic spline is fitted to the graph 700 of FIG. 7 to illustrate peaks of the flow velocity seen at the driving frequencies of 175 Hz, 350 Hz and 525 Hz.
10 Nevertheless a downward decreasing trend is observed (as the driving frequency increases), suggesting that increasing switching frequencies of the stages may lead to decreasing flow velocity of the air current. This concurs with the theoretical explanation, which sets out that an incorrect driving frequency may result in a larger number of phase-mismatched ions, resulting in the
15 deceleration of such ions and therefore leading to a decrease in flow velocity of the air current. It is to be appreciated that a peak of the flow velocity occurring at 175 Hz is relatively close to the predicted optimal driving frequency of 167 Hz, and therefore provides some validation for the theoretical analysis. Additional peaks of the flow velocity occurring at 350 Hz and 525 Hz, all being multiples of
20 175Hz, are likely due to harmonic effects, as already set out in the theoretical analysis. However, the readings measured are generally lower than in the case of the single-stage prototype, which may be attributed to increased length of the accelerating electrode array causing increased frictional losses, which occur at inner surfaces of the accelerating electrode array.

25 A 3-stage prototype (of the device 300) and a 4-stage prototype (of the device 300) were also evaluated. Based on the results respectively shown in graphs 800, 900 in FIGs. 8 and 9, it is to be appreciated that the 3-stage prototype and 4-stage prototype are observed to exhibit higher flow velocity readings of the air
30 current generated compared to the single-stage prototype, which suggests that although the 2-stage prototype may not be as efficient as the single-stage prototype due to increased length of the accelerating electrode array, any fluid losses are compensated by increased accelerating distance of higher-staged prototypes. The 3-stage prototype and 4-stage prototype also yield similar
35 peaks of flow velocity occurring in the vicinity of 175 Hz, as well as lesser peaks

in their respective harmonics, providing further validation for the theoretical analysis.

FIG. 10 is a graph 1000 which superimposes all the data sets of FIGs. 6-9 and the respective linear regression lines, in which it is apparent that the flow velocity of the 4-stage prototype exceeds the flow velocities of the other prototypes by a significant margin. The graphs of the 2, 3 and 4-stage prototypes are also observed to follow a downward decreasing trend with a substantially similar graph gradient, in accordance with the theoretical analysis. Due to a marked increase in flow rate at a particular driving frequency, as well as presence of a distinct peak, it may be determined that the oscillating electric fields generated by the accelerating electrode array arranged with multi-stages are indeed responsible for the observed increased and thus provide a significant improvement over conventional designs which uses an electrostatic field configuration.

A 10-stage prototype (of the device 300) was also implemented (i.e. see a photo 520 in FIG. 5c) using the specifications derived in the “*Theoretical Analysis*” section (i.e. see table 200 of FIG. 2). From a graph 1100 of FIG. 11, it is observed that flow velocity performance of the 10-stage prototype clearly outperforms the lesser-stage prototypes as above discussed in relation to FIGs. 6-9. Nonetheless, it is observed that airflow increases from additional stages included conversely decreases as the number of stages increases, likely due to retarding effects of an extended array length. Additional readings were then taken with the discharge and accelerating voltage, previously maintained constant, which were respectively increased to $V_0 = 5000$ V and $V_{stage} = 500$ V. The resulting data of flow velocity plotted against driving frequency, as depicted in FIG. 11, suggest that there is potential for significant improvements to be achieved with slight voltage increments.

• **Discussions**

The foregoing performance studies show that multi-stage prototypes of the device 300 offer significant improvements over the single-stage variants, and that additional stages do increase a maximum flow rate of the air current generated by the proposed device 300. Existing studies have primarily focused

on characterizing single-stage designs, and none incorporates a setup for generating an oscillating electric field. While the flow rate of air current generated by the single-stage prototype is not necessarily relevant to the conclusion that may be drawn from the studies, differences in flow rate between
5 the single-stage prototype and other conventional studies may be attributed to different study conditions, as well as using a different electrode design, which may significantly affect the flow rate of a solid-state fan. The difference in flow rate does not however detract from findings of the performance studies conducted on the prototypes of the proposed device 300, which clearly illustrate
10 that a multi-stage design (for the accelerating electrode array) generally outperforms a single-stage design.

It is however to be appreciated that the multi-stage prototypes seems to perform better with more stages compared to ones with fewer stages, regardless of a
15 period configured for generating the oscillating electric fields. This may be due to presence of a stronger electric field generated on average, thus leading to higher speeds of airflow, which may not be necessarily more energetically efficient than a single-stage design. There is a distinct and observable peak at approximately 167 Hz for all of the multi-stage prototypes, which supports the
20 theoretical analysis, but it may be possible for 167 Hz to be the optimum driving frequency to be imposed regardless of spacing distances arranged between the respective stages of the accelerating electrode array.

The significance of using a multi-stage design for the device 300 is that it allows
25 for higher airflow speeds to be achieved with using less bulky driving electronics and a lower operating voltage, in a situation where a single-stage design would fail due to risk of dielectric breakdown occurrence. It is important to note that the multi-stage design may be further optimized through use of different electrode designs or by changing a velocity flow profile, and thus has room for
30 improvement, possibly resulting in even higher speeds compared to single-stage designs. A more optimum spacing between the stages of the accelerating electrode array may also possibly lead to better performance. Hence, future research may be carried out to determine if more optimal configurations of electrode spacing exist, and to also measure static pressure and other variables
35 to more fully characterize the device 300.

For completeness, with reference to FIG. 12, it is to be appreciated that conventional designs make use of an electrostatic field to accelerate ions generated in a corona discharge. The corona discharge takes place at a discharge electrode 1200, and the electrostatic field established between the
5 discharge electrode 1200 and counter electrodes 1202 accelerates the ions such that the ions collide with air molecules, which results in bulk air flow. The counter electrode 1202 pairs may also be placed in series such that the outlet of one pair is fed into the inlet of another pair. However, each counter electrode 1202 pair is to be connected to a power source that is floating, electrically wise,
10 with respect to all other sources to prevent the ions from travelling down the potential gradient and subsequently decelerating.

In contrast, the proposed device 300 uses multiple sets of counter electrodes 306 (each fabricated based on a ring electrode design), where each counter
15 electrode 306 is configured to be driven at a time varying potential. This establishes an oscillating electric field aft of an ion generation region (in the vicinity of the discharge electrode 302) for accelerating the ions, relaying the ions from a set of counter electrode 306 to a next adjacent set of counter electrode 306 of the accelerating electrode array (i.e. see FIGs. 13a to 13c).
20 Switching of the oscillating electric field is configured to occur at a specific driving frequency such that the ions are arranged to constantly travel up a potential gradient set up within the accelerating electrode array. Specifically, the ions gain an amount of energy proportional to a number of stages of the accelerating electrode array the ions are accelerated through. This makes it
25 feasible to reduce an operating voltage of the device 300 while still maintaining/improving performance by increasing a number of stages to be included. Furthermore, using an oscillating electric field in the device 300 to generate air current reduces an amount of ions decelerated by the electric field, compared to using a static (non time-variant) electric field, which may
30 undesirably result in ions travelling up and down a potential gradient yielding a net zero useful energy gain. This thus makes it further feasible to use only a single power supply for the proposed device 300. So, generating an oscillating electric field through a setup of multi-stage counter electrodes 306 for generating air flow is an important feature of the proposed device 300.
35 Accordingly, the reduced requirements on the driving electronics device 308

advantageously allow the device 300 to be made more compact, safer and more robust. Consequently, the proposed device 300 overcomes technical difficulties faced by conventional designs, and may find multiple potential applications in the consumer, industrial, and mission-critical sectors.

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So in summary, a method of providing an air current using the proposed device 300 (which includes the ion generating device 302, at least the power source 304 and the plurality of counter electrodes 306 electrically coupled to the power source 304) comprises: generating an electrostatic field using the ion generating
10 device 302 to ionize air molecules; and configuring the at least one power source 304 to cause the counter electrodes 306 to generate respective oscillating electric fields to progressively increase a speed of the ionized air molecules to generate the air current.

15

• **Conclusion**

A systematic investigation on effects of various parameters on observed flow rates of air current generated by the device 300 was carried out, and the following observations are drawn from analysis of the data collected.

20

1. Careful considerations are to be taken for configuring the counter electrodes 306 with suitable electrode geometry to minimize obstructions to air current generated by the proposed device 300. Specifically, non-observance of this aspect may result in degradation of performance results obtained from particularly obstructive electrode designs, especially
25 when the accelerating electrode array is arranged in extended configurations.

25

2. In general, a prototype of the device 300 with a larger number of stages of the accelerating electrode array outperforms another similar prototype with a lower number of stages.

30

3. The length of an instrument tube, which is used to house stages of the accelerating electrode array, may cause a small decrease in measured flow rate of the air current generated by the device 300.

4. The driving frequency has a significant and quantifiable effect on the resultant flow rate of the air current generated, due to an increased

phase-misalignment of ionized air molecules at frequencies other than the optimum driving frequency.

5. The resultant flow rate of air current generated by the device 300 is dependent on the accelerating voltage and discharge voltage.

5 6. A significant increase in flow rate may be achieved by using an oscillating electric field to accelerate ionized air molecules.

7. An oscillating electric field accelerates the ionized air molecules, resulting in a higher flow velocity.

10 From the foregoing, it will be appreciated that experimental analysis performed on the device 300 provides empirical proof that the theoretical analysis is sound and correct. Through using oscillating electric fields in place of an electrostatic field, the proposed device 300 may achieve relatively high flow velocities for the air current generated and substantially high performance without using operating
15 voltages exceeding 10,000 V, thereby allowing a multi-stage oscillating electric field electro-hydrodynamic accelerator to be realised.

The proposed device 300 is revolutionary breakthrough in the field of research on electro-hydrodynamic accelerators, since the concept of using multi-stage
20 oscillating electric fields to accelerate ionized air molecules to generate air current, which beneficially enables a lower discharge voltage to be used, minimises the risk of dielectric breakdown occurrence in an atmospheric environment. It is to be appreciated that for the proposed device 300, discharging may be achieved using a voltage of less than or equal to -4500 V,
25 depending on a geometry adopted for the discharge electrode 302. Further, the driving electronics device 308 may be miniaturized significantly due to lower voltage demands placed on the power source 304, not to also mention that the lower voltage requirements reduce the risk of insulation breakdown or arcing, thereby preventing accidents occurrence and eliminating need for extensive
30 insulation of the power source 304. Consequently, the proposed device 300 is efficient, compact, and highly robust compared to conventional designs which instead use an electrostatic field to accelerate ionized air molecules. Envisaged useful applications of the device 300 include, for example, being incorporated as a portable electro-hydrodynamic accelerator in consumer electronics for
35 replacing conventional rotary electric fans.

The use of oscillating electric fields by the device 300 also permits the corona discharge current to be reduced without impacting on a flow rate of air current generated by the device 300, since the flow rate is no longer solely dependent on the acceleration provided by the electrostatic field (generated by the discharge electrode 302 and) used for corona discharge. Since ozone production is substantially linearly related to the corona discharge current, the ozone by-production may also be reduced for practical usage in consumer or sensitive hardware, or (if desired) conversely increased for integration into products where oxidising agents are necessary.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary, and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practising the claimed invention.

For example, it is to be appreciated that the counter electrodes 306 may adopt any suitable electrode geometry, and not limited to only the ring electrode design. Additionally, a geometry adopted for the discharge electrode 302 may also be optimized to provide better ionisation in conjunction with an associated electrode geometry used for the counter electrodes 306. Further, besides using a device which operates using negative corona discharge to generate the ionized air molecules, other suitable types of ion generating devices, such as RF plasma generators or the like, are also usable for the proposed device 300. More miniature versions of the counter electrodes 306 may also be used to reduce the drawbacks associated with having a lengthy accelerating electrode array. More precise fabrication techniques may be adopted for fabricating the counter electrodes 306, which may assist with eliminating erratic airflow in the accelerating electrode array, thus further improving performance of the proposed device 300. Moreover, the first and second voltage signals, to be applied to the counter electrodes device 308 to generate the oscillating electric fields, need not always be the accelerating voltage (of the driving electronics device 308) and ground potential; other suitable voltages may also be utilised. Yet further, each counter electrode 306 may be formed as a single contiguous ring electrode, or

may alternatively consists of a pair of half rings in opposing reciprocating arrangement, releasably assembled to form the ring electrode.

Claims

1. A device arranged to provide an air current, comprising:
an ion generating device configured to generate an electrostatic field to
5 ionize air molecules;
at least one power source; and
a plurality of electrodes electrically coupled to the at least one power
source configured to cause the electrodes to generate respective oscillating
electric fields to progressively increase a speed of the ionized air molecules to
10 generate the air current.
2. The device of claim 1, wherein the electrodes include being sequentially
arranged as respective stages, which are classified into odd and even stages.
- 15 3. The device of claim 2, wherein each stage includes a pair of electrodes in
opposing arrangement, and sequentially arranged includes being serially
arranged.
4. The device of claim 2 or 3, wherein a number of the stages include ten
20 stages.
5. The device of any preceding claims, wherein the ion generating device
includes a corona discharge ionization device or a RF plasma generator.
- 25 6. The device of claim 2, further includes a driving electronics device
electrically coupled to the at least one power source and electrodes, wherein the
driving electronics device is configured to transmit first and second signals to the
electrodes to cause the electrodes to generate the respective oscillating electric
fields.
30
7. The device of claim 6, wherein the driving electronics includes an
accelerating voltage power supply arranged to output an accelerating voltage
and, wherein the first and second signals respectively include the accelerating
voltage and a ground potential.
35

8. The device of claim 7, wherein the accelerating voltage is configured to be between 300 V to 500 V.

5 9. The device of any of claims 6 to 8, wherein the driving electronics device is configured to switchably transmit the first and second signals to between the odd and even stages respectively at a predetermined frequency.

10. The device of claim 9, wherein the predetermined frequency includes a frequency of 167 Hz.

10

11. The device of claim 3, wherein the stages in the serial arrangement are arranged into concentric rings.

12. The device of claim 2 or 3, wherein each stage is spaced from another
15 adjacent stage by a predetermined distance.

13. The device of claim 12, wherein the predetermined distance ranges between 5.00 mm to 6.12 mm.

20 14. The device of claim 1, wherein the ion generating device includes at least one discharge electrode configured to generate the electrostatic field.

15. The device of claim 14, wherein the discharge electrode is biased at a voltage of -4500 V.

25

16. A method of providing an air current using a device which includes an ion generating device, at least one power source and a plurality of electrodes electrically coupled to the at least one power source, the method comprises:

30 generating an electrostatic field using the ion generating device to ionize air molecules; and

configuring the at least one power source to cause the electrodes to generate respective oscillating electric fields to progressively increase a speed of the ionized air molecules to generate the air current.

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