



- (51) International Patent Classification:
F02K 9/80 (2006.01)
- (21) International Application Number:
PCT/US2015/045035
- (22) International Filing Date:
13 August 2015 (13.08.2015)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
62/037,043 13 August 2014 (13.08.2014) US
- (71) Applicant: UNIVERSITY OF FLORIDA RESEARCH
FOUNDATION INC. [US/US]; 233 Grinter Hall, Gaines-
ville, FL 32611 (US).
- (72) Inventor: SUBRATA, Roy; 8722 NW 9th Place, Gaines-
ville, FL 32606 (US).
- (74) Agents: GRIGGERS, Charles, W. et al.; Thomas I Hor-
stemeyer, LLP, 400 Interstate North Parkway, SE, Suite
1500, Atlanta, GA 30339 (US).
- (81) Designated States (*unless otherwise indicated, for every
kind of national protection available*): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,

HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States (*unless otherwise indicated, for every
kind of regional protection available*): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,
GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a
patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the
earlier application (Rule 4.17(iii))*

Published:

- *without international search report and to be republished
upon receipt of that report (Rule 48.2(g))*

(54) Title: PLASMA ACTUATED DRAG REDUCTION

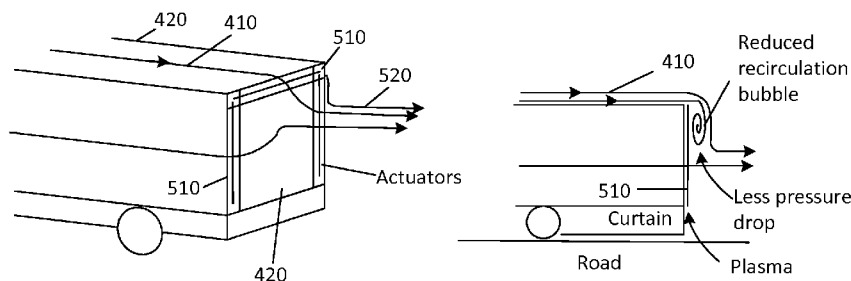


Figure 5

(57) Abstract: The present disclosure describes various embodiments of a plasma actuator device that can be affixed to a vehicle and configured to inject small turbulent structures to break down large vortical structures in a wake of the vehicle while in motion.

PLASMA ACTUATED DRAG REDUCTION

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to co-pending U.S. provisional application entitled "Plasma Actuated Drag Reduction" having serial number 62/037,043, filed on August 13, 2014, which is entirely incorporated herein by reference.

BACKGROUND

[0002] There is a considerable drag induced by the flat rear box-like ends of trucks and trailers, particularly when operated at relatively high speeds, such as 60 miles per hour (mph) and higher. This problem is not limited to the trucking industry. Railroad cars also transport trailers and cargo containers having a box shape. The railroad trailers and cargo containers present the same problem faced by the trucking industry with respect to aerodynamic drag during relatively high speed movement and increased fuel consumption that is a by-product of large aerodynamic drag.

SUMMARY

[0003] Embodiments of the present disclosure provide a system and method for aerodynamic drag reduction using one or more plasma actuators affixed to a vehicle.

[0004] An embodiment of the present disclosure provides for a system comprising a plasma actuator device affixed to a vehicle and configured to

inject small turbulent structures to break down large vortical structures in a wake of the vehicle while in motion. The system further includes a power source configured to supply power to the plasma actuator device. In various embodiments, the plasma actuator device comprises a serpentine plasma actuator.

[0005] An embodiment of the present disclosure further provides for a method comprising affixing one or more serpentine plasma actuators to a rear surface of a vehicle; and while the vehicle is in motion, activating the one or more serpentine plasma actuators to inject turbulent structures that are normal to the rear surface of the vehicle. Accordingly, the turbulent structures energize a wake flow of the vehicle creating a high pressure that acts on the rear surface and reduces aerodynamic drag.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0007] Figure 1 is a chart showing petroleum consumption in the United States.

[0008] Figure 2 is a graph showing a relationship between automotive horsepower consumption and automotive speed.

[0009] Figures 3-4 are diagrams depicting drag related energy loss at the rear end of a vehicle.

[0010] Figure 5 is a diagram showing a solution to drag loss in accordance with an embodiment of the present disclosure.

[0011] Figure 6 is a diagram of a straight-line plasma actuator in accordance with an embodiment of the present disclosure.

[0012] Figure 7 is a diagram of a serpentine or curved-line plasma actuator with at least one spiral electrode having hard angles in accordance with an embodiment of the present disclosure.

[0013] Figure 8 is a diagram of a serpentine or curved-line plasma actuator with at least one spiral electrode having soft angles in accordance with an embodiment of the present disclosure.

[0014] Figure 9 is a diagram depicting forces anticipated from the use of a serpentine actuator in accordance with an embodiment of the present disclosure.

[0015] Figures 10(a)-(f) are schematic diagrams of the generated body force for a DBD plasma actuator and linear, arc, rectangle, comb/finger, and triangle shaped serpentine actuators.

[0016] Figure 11(a)-(b) is a diagram of a tractor-trailer model with a serpentine plasma actuator in accordance with embodiments of the present disclosure.

[0017] Figures 12(a)-(c) are diagrams of particle image velocimetry (PIV) test results for near field flow inducement along a streamwise plane under quiescent conditions for linear and comb/finger shaped actuators according to various embodiments of the present disclosure.

[0018] Figure 13 is a diagram of particle image velocimetry (PIV) test results for near field flow inducement along a spanwise plane under quiescent conditions for comb/finger shaped actuators according to various embodiments of the present disclosure.

[0019] Figure 14 is a diagram showing an infrared image of the surface temperature around a serpentine actuator.

[0020] Figures 15(a)-(b) are a diagram of flow visualization at 30 mph showing changes in the trailing edge flow field with plasma being off and on.

[0021] Figures 16(a)-(c) are diagrams of drag measurements for linear and serpentine actuators according to various embodiments of the present disclosure.

[0022] Figures 17(a)-(f) are diagrams of drag reduction performance for serpentine actuators at a freestream velocity of 60 mph with continuous mode and amplitude modulation mode according to various embodiments of the present disclosure.

[0023] Figure 18 is a diagram showing a relationship between power consumption and drag reduction under the continuous mode and amplitude modulation mode according to various embodiments of the present disclosure.

DESCRIPTION

[0024] According to the United States Department of Transportation (DOT) and Federal Highway Administration (FHWA), the United States consumes 18.84 million barrels of petroleum per day, which is 21.6 % of the world's petroleum consumption. The United States produces only 9.5% of the world's petroleum. So, the U.S. depends on foreign countries for oil. In order to decrease the oil dependency, energy reduction and conservation methods are

critical. Transportation sector accounts for 67% of total U.S. petroleum usage. The division of U.S. petroleum use for the transportation sector can be seen in Figure 1. There are around 10.77 million heavy trucks registered and they travel approximately 140 billion miles on interstate highways and freeways in a year. These heavy trucks consume about 18% of the transportation petroleum which is approximately 12% of the total US petroleum usage.

[0025] Most of the energy consumed by the highway trucks is used to overcome aerodynamic drag and rolling friction. However, the power consumed to overcome the aerodynamic drag increases rapidly with increase in the speed of the vehicle as compared to the rolling friction. At highway speeds, a majority (65%) of this energy is consumed in overcoming the aerodynamic drag. The variation of power consumption with speed to overcome aerodynamic drag and rolling friction is shown in Figure 2. Incidentally, the crude oil price forecast for the year is \$118 per barrel. So, reducing the aerodynamic drag will not only save billions of dollars but will also make the U.S. less dependent on foreign oil. Available devices for drag reduction like boat tails, side skirts, curtains, side and roof extenders, gap fillers, splitter plates do not work well and come with significant implementation and usage penalty. Accordingly, embodiments of the present disclosure utilize plasma actuators for vehicle aerodynamic drag reduction at highway speeds.

[0026] The aerodynamic drag can be categorized into form drag and skin friction drag. The form drag is due to the size and shape of the object. Bodies with larger frontal area tend to experience more form drag than ones with less. Skin friction drag is due to the friction between the fluid and the surface of the body. It is known that as frontal area increases, the body will experience more

from drag than skin friction drag. For a vertical flat plate, the form drag is almost 100% while the skin friction is negligible.

[0027] The problem with a tractor-trailer is similar in nature. They have large frontal areas for both the tractor and the trailer. As a result, the drag experienced by the tractor-trailer is mostly due to the form drag. Streamlining the body to reduce the frontal area is one of the solutions to reduce the form drag, a technique that is generally used by car manufacturers. Similarly the tractors are now streamlined to reduce the form drag in front of the vehicle. The problem with the trailer, however, remains a challenge. The shape of a trailer is restricted due to cargo requirement. For any given dimensions, the box shape of a trailer has the highest volume. As a result, for allowing maximum cargo, the containers behind the truck (pulling the trailer) are not streamlined. This causes over 25% aerodynamic drag loss due to large wake recirculation trailing the truck costing huge fuel penalty (see Figure 3).

[0028] In general, the air that flows around a vehicle, such as an automobile, tractor-trailer, railroad car, etc., swirls around the rear of the vehicle while the vehicle is moving. These swirls are called vortices, and they represent a low-pressure area behind the vehicle. The low pressure behind the vehicle creates a suction effect that tries to pull the vehicle backwards. Therefore, reducing the size of the separation zone, which is the area behind the car containing the vortices behind the car, is one of the predominant methods of decreasing aerodynamic drag. The rear section of the vehicle is the cause of the most drag on a vehicle.

[0029] To address this issue, one embodiment of the present disclosure features a plasma actuated trailing edge of the trailer (see Figure 4). A focus

for such an embodiment is to minimize the large flow recirculation region that causes aerodynamic drag. In an embodiment, large vortical structures (in the large flow recirculation region) are broken down using serpentine type plasma actuators. These actuators are surface compliant, works with no moving parts, can be applied to the most receptive location, and responds to flow very quickly. In another embodiment, a plasma channel utilizing straight-line plasma actuators create an airflow that disturbs the surface flow of air that tends to create such large vortical structures and therefore also breaks down the large scale vortical structures in the flow recirculation region.

[0030] Therefore, embodiments of the present disclosure generate air flows that create several minor or small scale turbulences or vortices behind the vehicle instead of a large scale vortical structure thereby reducing aerodynamic drag. In particular, plasma actuators are used to generate small scale vortex structures that energize and stabilize the wake area behind a moving vehicle resulting in increased pressures acting on the bluff base area of the vehicle and thereby resulting in a reduced vehicle aerodynamic drag. To break the large vortical structures that can form in the wake of a moving vehicle, air flow surrounding the vehicle is turbulized instead of being attached or bent. A resulting benefit is that improved control in the turbulent flow regime is generated behind the moving vehicle, such as a tractor-trailer operating at 60 mph.

[0031] Non-limiting examples of plasma actuators are described in U.S. Patent No. 8,235,072, titled "Method and Apparatus for Multibarrier Plasma High Performance Flow Control," issued on August 7, 2012, U.S. Publication No. 2013/0038199, titled "System, Method, and Apparatus for Microscale Plasma

Actuation,” filed on April 21, 2011, and WIPO Publication No. WO/2011/156408, titled “Plasma Inducted Fluid Mixing,” filed on July 6, 2011. Each of these documents is incorporated by reference herein in its entirety. Non-limiting examples of plasma actuators that may be used in various embodiments include both curved-line actuators (open) or straight-line actuators within plasma channels (close) at sides of a vehicle that are affected by drag, including the trailing end of a vehicle (such as a vehicle pulling a transport trailer or cargo container).

[0032] Now referring to Figure 3 and Figure 4, the figures show flow patterns in the wake of a tractor-trailer truck without a plasma actuator solution installed, as a non-limiting example. In Figure 4, the airflow about the vehicle and in the base region is represented by arrow tipped lines 410 and swirl structures 415. The conical shaped structures with arrow tipped lines represent vortices 415 as part of a rotational wake flow. For this condition, a surface flow develops on the trailer 420 that separates at the trailing edge of the side surfaces, and forms rotational-flow structures 415 that comprise the bluff-base wake flow. The rotational-flow structures 415 are shed asymmetrically from the opposing side surfaces. These rotational-flow structures 415 continue to move downstream in a random pattern as the vehicle moves. The asymmetric shedding of the rotational-flow structures 415 produce low pressures that act on the base surface 430 of the trailer. These low pressures result in a high aerodynamic drag force. The low energy flow separating at the trailing edges of the side surfaces of the trailer is unable to energize and stabilize the low energy bluff-base wake flow. The resulting bluff-base wake-flow structure emanating from the base area 430 of the vehicle is

comprised of the vortex structures 415 that are shed from trailing edges of the side surfaces of the trailer. In this non-limiting example, Figure 4 shows a curtain or skirt wrapped around a bottom or undercarriage of the trailer to reduce the presence of a low-energy turbulent flow exiting from the vehicle undercarriage. However, embodiments of the present disclosure may also be utilized with vehicles without such skirts/curtains. In such embodiments, the low-energy turbulent flow that exits from the vehicle undercarriage at the base of the vehicle will contribute to the low-energy bluff-base wake at the rear of the vehicle/trailer. The unsteady wake flow imparts a low pressure onto the aft facing surface of the trailer base that results in significant aerodynamic drag. Accordingly, plasma actuators may be positioned and configured to act on the turbulent flow exiting from the vehicle undercarriage, in some embodiments.

[0033] Next, Figure 5 shows a perspective view and a side view of the aft portion of a trailer 420, with an embodiment of the plasma actuator solution installed, in a non-limiting example. The area designated by pointer 510 represents an area upon which plasma actuators may be installed or affixed, in certain embodiments. Systems according to the present disclosure may be constructed to be attached to a vehicle using different customizable attachment types, such as screws, rivets, hooks, hinges, glues, bolts, hook-and-loop fasteners (e.g., Velcro™), etc. on the market today or in the future.

[0034] In one embodiment, straight-line plasma actuators are positioned within one or more flow channels on a back surface 430 of a trailer. The flow of air generated by the plasma actuators flows vertically through an outlet port of a plasma channel that is defined by area 510. In some embodiments, plasma actuators may be positioned on a flat surface (e.g., a top surface of the trailer)

upstream of a trailing edge of the trailer/vehicle alternative to or in addition to plasma actuators positioned on the back surface.

[0035] During transport of the vehicle including the trailer 420, a surface flow develops on the trailer exterior top surface and exterior side surfaces. This surface flow is penetrated by the vertical flow induced by the plasma channel, in an embodiment. Accordingly, the vertical flow breaks up the surface flow. Therefore, instead of the surface flow, from over the top/sides of the trailer 420, creating a large pressure bubble at the wake of the vehicle (as described in Figure 3 and Figure 4), the flow generated by the plasma actuators will trip the surface flow, and the surface flow will collapse (as indicated by pointer 520) and attach to the surface of the vehicle (as shown in Figure 5) due to introduction of the vertical flow created by the plasma actuator channel, thereby reducing the aerodynamic drag.

[0036] In an alternative embodiment, instead of or in addition to plasma actuator channel(s) being installed on a surface of the vehicle 420, curved or serpentine plasma actuators are fastened or affixed to the vehicle surface. At onset of large vortical structure, the serpentine plasma actuators are configured to inject small turbulent structures to break down the large vortical structure. As a non-limiting example, serpentine plasma actuators may be installed to a back or rear surface of a cargo trailer (within area 510), as represented in Figure 5, for one embodiment. The serpentine plasma actuators are configured to generate small scale vortices that are normal to the back of the trailer. Therefore, while a vehicle 420 moves downstream, a plurality of small scale vortices may be generated at the trailing edge of the vehicle, which will energize the wake flow of the vehicle, and thereby create a

high pressure that acts on the back surface 425 of the trailer and reduces aerodynamic drag. By utilizing spherical or curved plasma actuators to generate vortex structures that energize the bluff-base wake of a moving vehicle, embodiments of the present disclosure can help reduce aerodynamic drag.

[0037] In this example, Figure 5 shows a curtain or skirt wrapped around a bottom or undercarriage of the trailer to reduce the presence of a low-energy turbulent flow exiting from the vehicle undercarriage. However, embodiments of the present disclosure may also be utilized with vehicles without such skirts/curtains. In such embodiments, the presence of the serpentine plasma actuators improves mixing of the undercarriage flow with the bluff-base wake. The vortex structures energize and stabilize the wake resulting in reduced unsteady flow separation, increased pressures acting on the bluff base area and reduced vehicle aerodynamic drag.

[0038] In accordance with the present disclosure, the above-described plasma actuators are surface compliant and can be applied to receptive locations on a vehicle or cargo container/trailer. For example, plasma actuators are not limited to being positioned within area 510 of Figure 5. Additionally, plasma actuators in accordance with the present disclosure require low power, can work at extreme temperatures (e.g., low temperatures) and are responsive to generating air flow very quickly upon being activated. Further, the above-described plasma actuators are non-intrusive to the surrounding air flow unless activated or turned on. Certain embodiments of the present disclosure can be configured to activate automatically based on detected conditions, such as vehicle or air speed, or may be activated manually, such as by driver

command. Accordingly, embodiments of the plasma actuator solution of the present disclosure are characterized by and associated with inexpensive costs, having low maintenance, being lightweight, and providing ease of operation.

[0039] For the plasma actuators, one embodiment can incorporate electrode pairs separated by an insulating material (see Figure 6). One embodiment can maintain the electrode pairs at a potential bias using steady, pulsed direct, or alternating current. In an embodiment, renewable energy sources may be used as a power source for the plasma actuators. For example, solar panels may be affixed to the walls or sides of a vehicle, trailer, or cargo container and used to power the plasma actuators or recharge batteries used to power the plasma actuators, in one embodiment. Further, in an embodiment, wind energy extractors, such as a wind turbine, may be affixed to a side, bottom, back, or other surface that receives air flow and be used to collect energy that is used as a power source for the plasma actuators or associated batteries. Associated components, such as power converters and inverters, are also utilized in certain embodiments.

[0040] In accordance with certain embodiments of the present disclosure, a plasma actuator incorporates at least one pair of electrodes positioned on one or more surfaces of a vehicle or cargo container to create a plasma channel. When a voltage potential is applied across one of the at least one pair of electrodes a plasma discharge is produced that induces air flow in the plasma channel. In an embodiment, when the plasma discharge is produced an electrohydrodynamic (EHD) body force is generated which induces air flow in the plasma channel. In a further embodiment, a plurality of such actuators is used. A voltage potential can be applied to each actuator in timed phases.

For example, three or more electrodes can be positioned in the plasma channel and powered in phased pairs, in one embodiment.

[0041] As discussed, in certain embodiments, a serpentine plasma actuator can incorporate a pair of electrodes, where at least one of the pair of electrodes has a serpentine shape. The at least one serpentine electrode can have one or more of turns. In an embodiment, when the serpentine plasma actuator is powered at least one plasma discharge is produced in a fluid, such as air surrounding a vehicle. In an embodiment, each at least one plasma discharge induces at least one force in the fluid. In an embodiment, each of the at least one force is an EHD body force. The at least one force can create turbulence in the fluid. In an embodiment, the at least one force generates one or more flow structures in the fluid. In a particular embodiment, one or more counter-rotating vortex pairs (CVPs) are generated in the fluid.

[0042] The electrodes of the pair of electrodes can be located such that a constant distance is maintained between the two electrodes. In an embodiment, the at least one serpentine electrode is formed with a plurality of turns. In an embodiment, the turns include hard angles as shown in Figure 7. In an embodiment, the turns include softer curves as shown in Figure 8. In other embodiments, the turns can include hard angles, softer curves, and/or other types of turns. In an embodiment, the turns are confined to two dimensions such that the serpentine electrode can be contained within a plane. In another embodiment, the turns encompass three dimensions. In an embodiment, each of the pair of electrodes is formed with one or more turns. In an embodiment, each of the pair of electrodes is formed with a plurality of turns. In an embodiment, at least a portion of each of the pair of electrodes

has the same pattern of turns, such that for each turn in a portion of a first electrode of the pair there is a corresponding turn in a corresponding portion of a second electrode of the pair. In an embodiment, the corresponding turns are in the same order on each of the electrodes. In an embodiment, each of the turns on one electrode of the pair are spaced approximately the same distance apart from each other as the corresponding turns on the other electrode of the pair. In an embodiment, the electrodes are positioned parallel to each other in the same plane. In an embodiment, the turns of the electrodes are in phase such that each of the corresponding turns is made in the same direction, as shown in Figures 7 and 8. In another embodiment, the turns are out of phase with each other. In an embodiment, each of the corresponding turns is made in an opposite direction. In a further embodiment, the turns are formed in three dimensions. In an embodiment, the electrodes are spatially aligned such that the corresponding turns are proximate to each other. In an embodiment, when the serpentine plasma actuator is powered at least one plasma discharge is produced in the fluid. In an embodiment, each at least one plasma discharge induces at least one force in the fluid. In an embodiment, each of the at least one force is an EHD body force. In an embodiment, the at least one force creates turbulence in the fluid. In an embodiment, the at least one force generates one or more flow structures in the fluid as discussed above. In a particular embodiment, one or more CVPs are generated in the fluid.

[0043] Figure 9 depicts forces anticipated from the use of a serpentine actuator in accordance with an embodiment of the present disclosure. In an embodiment, the top electrode can be grounded and the bottom electrode can be powered to achieve a voltage potential. In an alternative embodiment, the

bottom electrode can be powered and the top electrode can be grounded. In an alternative embodiment, both electrodes are powered to achieve the voltage potential. When the voltage potential is achieved, plasma discharges can be produced in a fluid, such as air, proximate to the actuator. As discussed above plasma discharges can generate forces that act on the fluid. The arrows shown in Figure 9 indicate anticipated forces produced by the depicted actuator. As shown, the anticipated forces alternately exert pinching (inward) and spreading (outward) forces on the fluid. In an embodiment, plasma actuators such as the plasma actuators described herein produce forces in three dimensions.

[0044] In a particular embodiment, plasma discharge is created in the fluid as the fluid passes over the actuator and the fluid receives forces from a plurality of directions such that the fluid collides and mixes. In an embodiment, the forces produce pinching (inward) and/or spreading (outward) effects on the fluid as the fluid passes over the actuator. In an embodiment, the actuator produces forces in the direction of the fluid flow over the actuator (streamwise), orthogonal to the direction of fluid flow and parallel to the surface of the actuator (crosswise), and/or orthogonal to the direction of fluid flow and perpendicular to the actuator surface (surface normal). In an embodiment, the actuator produces both streamwise and crosswise forces. In another embodiment, the actuator produces both streamwise and surface normal forces. In yet another embodiment, the actuator produces both crosswise and surface normal forces. In a further embodiment, the actuator produces streamwise, crosswise, and surface normal forces. The paper by Roy S. and Chin-Cheng Wang, "Bulk Flow Modification with Horseshoe and Serpentine

Plasma Actuators," J. Phy. D: Appl. Phys. 42 (2009) describes simulations of flows produced by such actuators and is incorporated herein by reference in its entirety. In a further embodiment, the forces generate one or more flow structures in the fluid, such as the vortical and other flow structures discussed above.

[0045] For the present disclosure, at least one power source can be provided for powering the electrodes. In an embodiment, the pair of electrodes includes a grounded electrode and a powered electrode, which is powered to achieve the voltage potential. In an alternative embodiment, both electrodes of the pair are powered at different voltages to achieve the voltage potential. In various embodiments, alternating current (AC) and/or direct current (DC) power sources can be used. In an embodiment, electrodes pairs on the same surface or layer are maintained at a potential bias using steady, pulsed direct, or alternating current. Electrode pairs can be separated by an insulating material where one electrode of the pair is powered with DC or AC operating at a radio frequency (RF) with respect to the other. In an embodiment, a powered electrode of the pair is powered at RF voltages, while a grounded electrode of the pair is grounded. In an alternative embodiment, both electrodes are powered with signals separated by a beat frequency.

[0046] In an embodiment, the plasma actuators may be activated by applying voltages with various types of waveforms across the respective first electrodes and second electrodes. For example, the plasma actuators may be activated by applying a constant voltage across the respective first electrodes and second electrodes. As another example, a sinusoidal voltage may be applied to the plasma actuators or a square-wave voltage may be applied.

Additionally, each one of the plasma actuators may be individually activated and deactivated according to a predefined pattern. In an embodiment, the air flow induced in the flow passage can be varied by controlling the applied voltage potential, phase angle, and/or frequency across each one of these actuators.

[0047] As an example, a serpentine plasma actuator may be activated by applying voltages with various types of waveforms across a first spiral electrode and a second spiral electrode. For example, a constant voltage may be applied across the respective first spiral electrode and the second spiral electrode. As another example, a sinusoidal voltage may be applied across the first spiral electrode and the second spiral electrode or a square-wave voltage may be applied. As a result of a voltage being applied across the first spiral electrode and the second spiral electrode, an EHD body force may be induced in multiple directions. For embodiments in which the voltage waveform is sinusoidal or pulsed, for example, the EHD body force may also be sinusoidal or pulsed. Such resulting EHD body forces may generate waves in the fluid in which the serpentine plasma actuator is located.

[0048] In an embodiment, pairs of electrodes or actuators are powered in parallel (i.e., at the same time) to generate multiple plasma discharges within a flow passage at the same time. In another embodiment, pairs of electrodes or actuators are powered in series to generate sequential plasma discharges within the flow passage. In yet another embodiment, pairs of electrodes or actuators are powered in both parallel and sequential groupings. A particular electrode, among the plurality, can be paired with a first electrode, among the plurality, to generate a first plasma discharge. Later, the particular electrode

can be paired with a second electrode, among the plurality, to generate a second plasma discharge.

[0049] Next, experimental data collected for linear and serpentine plasma actuators under quiescent operating conditions show that the serpentine design has profound effect on near wall flow structure and resulting drag. For certain actuator arrangements, the measured drag reduced by over 14% at 60 mph and over 10% at 70 mph opening up realistic possibility of reasonable energy savings for full scale ground vehicles. The power consumption data for different input signals are also presented in the experimental data discussed below.

[0050] As discussed, the presence of viscous drag limits the fluid dynamic performance of any vehicle. For example, the viscous drag may comprise upwards of 50%, 65% and 70% of the total drag for commercial air vehicles, heavy highway vehicles, and high speed trains, respectively. Hence, any method for reducing this drag, including but not limited to controlling surface receptivity and fluidic actuation, can have profound influence in transportation applications. Previously, plasma actuators for improving authority of flow control have had limited success due to their inherent near wall momentum/heat injection method. Such actuators produce a high gradient at the wall limiting an effective control. Efforts have also been invested in influencing the drag, specifically turbulent drag, using plasma actuators.

[0051] For example, a standard straightedge dielectric barrier discharge (DBD) actuator employs an exposed electrode and an asymmetrically displaced encapsulated electrode to generate a directional plasma body force due to the surface discharge. The power budget associated with these

actuators is 10-100 watts per meter length of the actuator. As the discharge expands along the dielectric surface, momentum is transferred from ions in plasma to the surrounding fluid, generating a Glauert-like “wall jet” very close to the work surface. This wall jet also produces a large streamwise velocity gradient and a resulting roll-up streamwise vortex structure downstream of the actuator far beyond the encapsulated electrode resulting in an interaction with the neighboring flow. This wall jet has been investigated for momentum addition applications, such as flow separation control over airfoils and turbine blades, and for boundary layer manipulation. Various parametric studies have focused on increasing the velocity and momentum transfer of this wall jet. The capability of such actuators is often quantified by the velocity ratio, which is the ratio of the induced jet velocity to the velocity of the bulk flow, and is limited by their associated skin friction drag. In fact, application of a standard actuator for drag reduction at lower velocities may be counterproductive as the induced wall jet introduces more wall shear. However, the challenge is more daunting at higher velocity (and velocity ratios) when the influence of induced wall jet and a majority one-dimensional vortical structure fails to control the flow streaks.

[0052] Contrarily for a serpentine actuator, the induced flow is vectored at an angle away from the surface and due to simultaneous pinching and spreading effects on the neighboring flow a fully three-dimensional vortical structure rapidly turbulizes the flow thickening the boundary layer. General shapes of serpentine actuator are shown in, but not limited to those shown in, Figures 10(a)-(f). In particular, Figure 10(a) depicts a schematic of a DBD plasma actuator and the generated body force. Figure 10(b) depicts a linear plasma

actuator. Figure 10(c) depicts a serpentine plasma actuator in the shape of a curved arc. Figure 10(d) depicts a serpentine plasma actuator in the shape having a rectangle geometry. Figure 10(e) depicts a serpentine plasma actuator having a comb/finger geometry. Figure 10(f) depicts a serpentine plasma actuator having a triangle geometry.

[0053] An interesting outcome of serpentine actuation is the capability of introducing periodic hairpins and possibly controlling the flow streaks by changing the wavelength and/or the amplitude of the serpentine geometry. This results in a useful control mechanism for aerodynamic drag for which the traditional actuators fails to show any beneficial effect.

[0054] Specifically for a three-dimensional tractor-trailer geometry, the drag is almost equally distributed into the frontal drag, skin friction drag (along large flat surfaces), under carriage drag (underneath the trailer body), and the pressure drag (behind the trailer). Skin friction drag is due to the friction between the fluid and the surface of the body. The tractor-trailer truck has large frontal area for both the tractor and the trailer. While streamlining the frontal area helps reducing the frontal drag, the box-like trailer designed to maximize cargo space remains a challenge for drag reduction. This is due to a large pressure drag from the trailing wake region that causes nearly majority of the aerodynamic drag related loss costing huge fuel penalty.

[0055] The serpentine class of dielectric barrier discharge actuator is introduced for effectively modifying aerodynamic drag for three-dimensional vehicle geometry. Specifically, drag reduction of a 1:60 scale tractor-trailer truck model at highway speeds of 60 and 70 mph (26.8 and 31.3 m/s, respectively) is demonstrated. Based on the geometry of the vehicle, the flow

is turbulent at these velocities. Recent reports on plasma actuation show various levels of success for flow control. For example, in a 1.75 m/s flow over a flat plate, the skin friction drag has been estimated to reduce by up to 45% by inducing spanwise oscillation and spanwise travelling wave using plasma actuators. For flow over a backward facing step geometry, the influence of flow actuation on the Reynolds stress have also been reported using standard linear plasma actuator (under 15 m/s) and serpentine actuator (under 20 m/s). However, all these experiments were done at low flow speeds over relatively simple geometries. To our knowledge, successful demonstration of vehicular drag reduction using plasma actuators at highway speeds has not been reported before.

[0056] For experimental testing, an open circuit low speed wind tunnel with a cross-section of 305 mm × 305 mm is used. The length of the test section is 610 mm. The front end of the truck is placed around 38 mm inside the nozzle leaving around 380 mm after the truck. The total aerodynamic drag from skin friction and pressure is measured directly using a two-axes thrust balance. The wind tunnel is fitted with a 2-axis force dynamometer. Two Shaevitz Sensors LVDT voltage modules are used to record the lift and drag with a precision of 5 mN. The analog output from the dynamometer is read using a LabVIEW interface.

[0057] For experimental testing, a straightedge "linear" actuator and a serpentine actuator are investigated for drag reduction. In both cases, the encapsulated electrodes are made from a thick copper tape, and the dielectric materials used are thick acrylic. These actuators are placed on the top and side surfaces with the ground electrode 5 mm from the trailing edge of the

truck (see Figure 11). The serpentine actuator geometry is similar to that described in Figure 10(e) with wavelength $\lambda = 5$ mm and amplitude $A = 7.5$ mm. It is important to note that since the actuators are located near the tail-end of the trailer, their resulting influence is assumed primarily on the pressure drag behind the truck.

[0058] The fluid-thermal performances of these actuators are compared in a quiescent chamber with dimensions $0.61 \times 0.61 \times 1.22$ m using a particle image velocimetry (PIV) system and an infrared (IR) imaging system. A Phantom v7.3 high speed camera in combination with a 105 mm macro-lens was employed to capture PIV images. The camera was aligned perpendicular to the laser light sheet with a distance of 0.5 m. The field of view captured for each image was approximately 45×60 mm. The light sheet cutting the actuators was generated using a Nd : YAG dual cavity pulsed 532nm laser (New Wave Research Solo PIV II 30). Seeding for PIV was generated by a TSI atomizer (Model 9302) with Ondina oil. When the atomizer was pressurized at 25 psi, the mean diameter of the oil droplet is about $0.8 \mu\text{m}$ [12]. DaVis 7.2 imaging and post processing software was used to capture and analyze PIV images. A FLIR A325 camera with standard built-in 25° lens was employed to capture the IR temperature image of the actuator. LabVIEW codes were utilized to record force, peak-to-peak voltage and current measurements from a Tektronix DPO3014 oscilloscope. This model has a maximum sampling rate of 2.5 GSa/s at a bandwidth of 100 MHz. Voltage is measured using a Tektronix (Model P6015A) passive probe having an attenuation of 1000x. The frequency response of the probe is able to measure AC voltages up to 40 kV with a rated accuracy of $\pm 3\%$. Current is measured

with a Pearson Electronics (Model 2100) inductive coil type current probe. This probe has a manufacturer rated accuracy of $\pm 1\%$ and a 20MHz bandwidth. A sinusoidal output signal generated in a Tektronix arbitrary function generator (Model AFG3022B) is passed through a QSC audio amplifier (Model RMX 2450), and then through a custom Corona Magnetics Inc. high voltage transformer to step up the voltage to the desired levels.

[0059] The PIV experiments are performed in quiescent condition to elucidate the difference between the two distinct types of actuators, namely, the linear actuator with straight edge and the serpentine actuator with comb like fingers. Figures 12(a)-(c) show a PIV test result comparison for near field flow inducement along the streamwise plane under quiescent condition for (a) Linear, (b) Serpentine between fingers, and (c) Serpentine along the finger.

[0060] The result for the linear actuator plotted in Figure 12(a) shows a known wall jet pattern that expands slightly due to the backward step at the trailing edge. The induced velocity (majorly streamwise) is about 3.5 m/s at 24 kV_{pp} and 5 kHz. The difference between the standard linear and the comb-shaped serpentine design is clearly demonstrated in Figures 12(b)-(c). The periodic finger structure allows pinching and spreading of the neighboring fluid rapidly inducing three-dimensional vortices similar to previously reported results. Distinctly, the flow field between the fingers demonstrates the effect of pinching in Figure 12(b) and that of spreading in Figure 12(c). Note that both these effects are somewhat modified by the presence of the backward step. However, a quick comparison between Figure 12(a) and Figure 12(b) shows a larger vertical spreading due to serpentine actuation downstream of the truck trailing edge. This indicates that serpentine actuator should have a stronger

influence in the wake region of the truck. Note that the average error considering both statistical and device error for PIV result is about 5%.

[0061] PIV measurements were also done along three spanwise cross-sections. These are depicted in Figure 13 which illustrates the PIV test result for near field flow inducement along the spanwise plane under quiescent conditions. In the figure, 1, 2 and 3 denote the cross-section planes where the PIV measurements were carried out.

[0062] The vectors in these figures are constructed using three times the spanwise velocity v_z and the normal velocity v_y . This is done to clearly show the pinching and spreading locations generated by the actuator. It shows that there is strong pinching effect at the fingers and spreading between them. This is unlike the circular-arc serpentine actuators where the flow is pushed up at the pinching location and accelerated forward in the spreading location. This is due to the fact that the pinching location is really small (finger thickness 2mm) which does not allow room for the flow to be lifted. Thus the momentum created by the downward pinching force at the fingers is balanced by the upward momentum created in between in fingers. It should also be noted that a strong spanwise component of velocity is generated, which is about 6 % of the streamwise component. This helps in the formation of streamwise oriented vortices which are essential in flow control.

[0063] The IR data under quiescent conditions are collected using a FLIR camera and corrected with the surface emissivity. The final temperature data, as plotted in Figure 14 (i.e., an IR image of the surface temperature around the serpentine actuator), shows a maximum temperature of about 48°C at the tip of the fingers where incidentally the electric field is also the maximum. The

surface temperature is within 30-35°C for the rest of the actuator. These temperature ranges will not have any significant effect on the flow field.

[0064] The flow visualization results at 30 mph (13.4 m/s) presented in Figure 15 show significant change in the trailing edge flow field. As compared to the baseline no plasma case in Figure 15(a), the trailing edge wake structure shows approximately 30% reduction in size in Figure 15(b) with plasma on. This change may positively influence the resulting pressure drag. Despite more dramatic changes at higher speed this effect was harder to record due to lack of sufficient number of seeding particles.

[0065] The drag measurement procedure in the wind tunnel is as follows. First, data logging from the force balance is set to collect data for 60 seconds at a sampling rate of 10 Hz while the wind tunnel is running. Thereafter, the function generator is switched on to predefined voltage and frequency settings. After the function generator is switched off, the dynamometer continues to send force data to the computer for another 60 seconds. These 60-second buffers are used to ensure that the transient responses of the system do not affect the beginning or end of the sampled data. The buffer time also provides a good estimate of the baseline drag against which the change is referenced. For the straightedge (linear) actuator, drag results for two voltages are reported, while for serpentine actuator, data for a range of voltages is presented. All plasma tests are done at 5 kHz for continuous mode using sinusoidal signal. For AM (amplitude modification) mode, a 125 Hz duty cycle is imposed over the continuous mode.

[0066] Drag measurements for the linear and serpentine cases are plotted in Figures 16(a)-(c). For Figure 16(a), linear actuators run for freestream velocity

of 60 mph showing drag increase for both continuous mode and amplitude modulation mode. For Figure 16(b), serpentine actuators run for freestream velocity of 60 mph. For Figure 16(c), serpentine actuators run for freestream velocity of 70 mph.

[0067] The average error for drag force is within $\pm 1\%$ of the measured drag. Interestingly, in Figure 16(a), the result shows a 5.1% increase of the measured drag using the linear actuator in continuous mode at 60 mph (26.8 m/s) while in amplitude modification (AM) mode the drag increases by 4.2%. In comparison, serpentine actuator result shown in Figure 16(b) documents a reduction in drag by 14.8% at 60 mph (26.8 m/s) and 10.4% at 70 mph (31.3 m/s).

[0068] It is estimated that serpentine actuator induces momentum transport in wall turbulence. This begins with near-wall quasi-streamwise vortices in the buffer layer producing hairpin vortices that auto-generate to produce packets of hairpins containing long, low-momentum zones in the logarithmic layer with and without the influence of thermal energy addition. Evidence indicates that substantial drag reduction is accomplished if the auto-generation mechanism is disrupted or inhibited by weakening the hairpin legs. It is also known that substantial intensification of the near-wall momentum transport delays flow separation by encouraging the mechanisms of leading hairpin formation and subsequent auto-generation of hairpins with proper sequences of actuator stimulation. Stimulation of small scales by plasma actuators may found its heightened effects when keyed to the large-scale motions. By knowing which perturbations will be most amplified, the geometry and operation of the

actuators (i.e. flow control devices) can be tailored specifically to excite modes for maximal flow control.

[0069] Figures 17(a)-(f) show the drag reduction comparison between AM mode and continuous mode for different voltages at 60 mph. For Figure 17(a), It is estimated that the AM mode will perform better than the continuous mode if higher (> 30 kV) voltage is used. The limitation here was due to the insulation and the amount of heat generated which could melt the thin copper electrode. For the continuous mode and the AM mode the drag reduction % increases as the voltage goes higher. The slope of increase in drag reduction % from 20 kV to 22 kV is much higher than from 22 kV to 24 kV for the continuous mode. However, the AM mode shows the same slope of increase.

[0070] The drag measurements for the truck with the linear and serpentine actuators are compiled in Table 1 (Actuation performance comparison on drag reduction at a freestream velocity V_{fs}). It is important to point out the comb-shaped serpentine actuator geometry with double the wavelength (results not shown for brevity) has been tested for which virtually no effect on the aerodynamic drag has been observed for flow speed above 30 mph. Based on theoretical study, the wavelength of the serpentine actuator is dependent on the flow parameters, namely, Reynolds number and flow streaks. As the free stream flow velocity increases smaller wavelength (reduced gap between the fingers) of the actuator becomes necessary to tune more flow streaks.

[0071] Relations between power consumption and drag reduction are also investigated under different running modes. As shown in Figure 18, under both continuous mode and AM mode, the drag reduction % increases when power consumption increases. One can also notice that although the peak to

peak voltage is higher for AM mode, the power consumption of AM mode is much lower than that of continuous mode. In Figure 18, it is also shown that the actuator only consumes 3.1 W to reduce 9.1 % of total drag with an AM input signal at 26 kV_{pp} while it consumes 4.3 W to reduce 8.9 % of total drag under a 20 kV_{pp} continuous input signal. From the data shown in Figure 18, the average effectiveness of both running modes can be calculated as drag reduction % per watt power consumed. For the AM signal, the actuator can reduce 2.7 % total drag per watt power consumed. With the continuous signal, 2.1 % total drag can be reduced per 1 W power consumed by the actuator.

V _{fs}	Voltage (Mode)	Linear Plasma Actuation	Serpentine Plasma Actuation
60 mph	20 kV _{pp} (Cont)		-8.9%
60 mph	22 kV _{pp} (Cont)		-12.9%
60 mph	24 kV _{pp} (Cont)	+5.1%	-14.8%
70 mph	24 kV _{pp} (Cont)		-10.4%
60 mph	26 kV _{pp} (AM)		-9.1%
60 mph	28 kV _{pp} (AM)		-10.5%
60 mph	30 kV _{pp} (AM)	+4.2%	-12.4%
70 mph	30 kV _{pp} (AM)		-6.4%

Table 1

[0072] The power saving from drag reduction is calculated using $P_{\text{saved}} = P_{\text{drag}} - P_{\text{elec}}$, where P_{drag} is calculated using $P_{\text{drag}} = \text{Drag force reduction} \times \text{Freestream velocity}$. The measured power consumption P_{elec} for serpentine plasma actuation with 24 kV_{pp} at 5 kHz in continuous mode operating under 60 mph free stream air velocity is 7.1 W as given in Table 2 (Power consumption data and full scale projection for serpentine actuator). Despite a 14.8% reduction, the drag power reduction is only 1.5 W for this 1:60 truck model.

Under the assumption that the actuator effectiveness remains essentially similar, the electrical power consumption should scale up with the length of the actuator (1:60) while the drag power reduction should scale with the surface area (1:3600). Thus, for a full scale truck, the electrical power consumption of the actuator and the drag power reduction are estimated to be about 400 W and 5400 W, respectively.

	Measured power for Truck Model	Scaling factor	Estimated power for a full scale truck
Electrical Power, P_{elec}	7.1 W	1:60 (1:l)	~426 W
Drag power reduction, P_{drag}	1.5 W	1:3600 (1:l ²)	~5400 W
Saved Power, P_{saved}	-4.6 W		~5000 W

Table 2

[0073] The experimental testing demonstrated a reduction of aerodynamic drag for a scaled tractor-trailer model at 60 mph and 70 mph using serpentine dielectric barrier discharge actuator. While a comparable size linear plasma actuator fails to modify the drag at these speeds, a specific serpentine actuator arrangement tuned to flow streaks reduced the total aerodynamic drag by nearly 15% at 60 mph and over 10% at 70 mph air flow in a wind tunnel. The foregoing examples of experimental testing are further explained in a paper entitled "Serpentine Dielectric Barrier Discharge Actuator for Vehicle Drag Reduction," by Subrata Roy, Pengfei Zhao, Arnob DasGupta, and Jignesh Soni, Applied Physics Research Group, Department of Mechanical & Aerospace Engineering, University of Florida, Gainesville, Florida 32611, USA, which is incorporated by reference herein in its entirety.

[0074] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations, merely

set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure.

CLAIMS

Therefore, at least the following is claimed:

1. A system comprising:
a plasma actuator device affixed to a vehicle and configured to inject small turbulent structures to break down large vortical structures in a wake of the vehicle while in motion; and
a power source configured to supply power to the plasma actuator device.
2. The system of claim 1, wherein the plasma actuator device comprises a serpentine plasma actuator.
3. The system of claim 2, wherein the serpentine plasma actuator comprises a comb/finger shaped actuator.
4. The system of claim 2, wherein the serpentine plasma actuator comprises a circular arc shaped actuator.
5. The system of claim 1, wherein the plasma actuator device comprises a plasma channel utilizing a straight-line plasma actuator.
6. The system of claim 1, wherein the power source comprises a renewable energy source affixed to an outside of the vehicle.

7. The system of claim 6, wherein the renewable energy source comprises a solar panel.

8. The system of claim 6, wherein the renewable energy source comprises a wind turbine.

9. The system of claim 1, wherein the vehicle comprises a tractor-trailer.

10. The system of claim 1, wherein the vehicle comprises a railroad trailer.

11. The system of claim 1, wherein the plasma actuator is affixed to a back surface of the vehicle.

12. The system of claim 1, wherein the plasma actuator is affixed to a side surface of the vehicle.

13. The system of claim 1, wherein the plasma actuator is affixed to a bottom or top surface of the vehicle.

14. The system of claim 1, wherein the plasma actuator is activated by applying a constant voltage across respective electrodes of the plasma actuator.

15. The system of claim 1, wherein the plasma actuator is activated by applying a sinusoidal voltage across respective electrodes of the plasma actuator.

16. The system of claim 1, further comprising a second plasma actuator, wherein each of the plasma actuators is individually activated and deactivated according to a predefined voltage pattern applied to the plasma actuators.

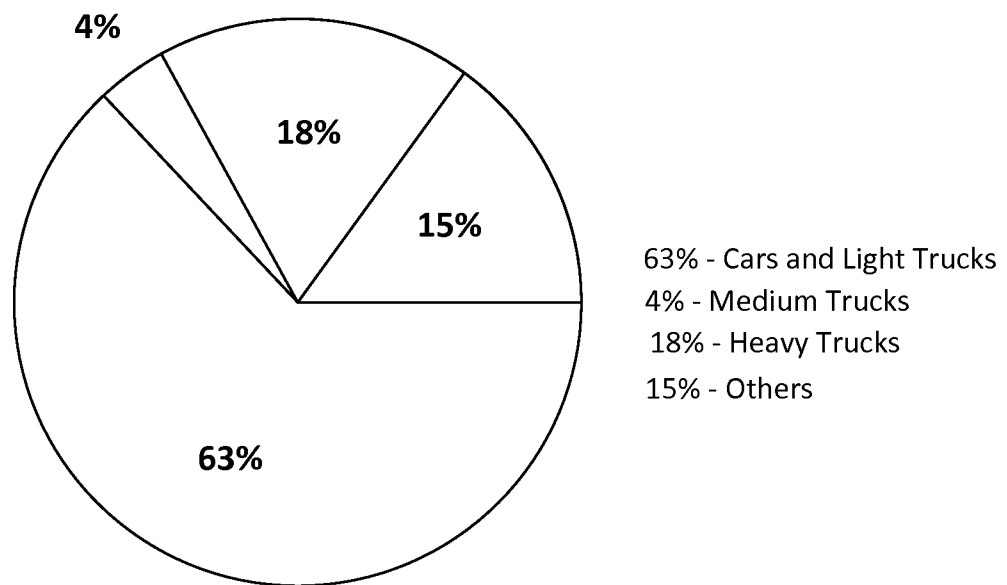
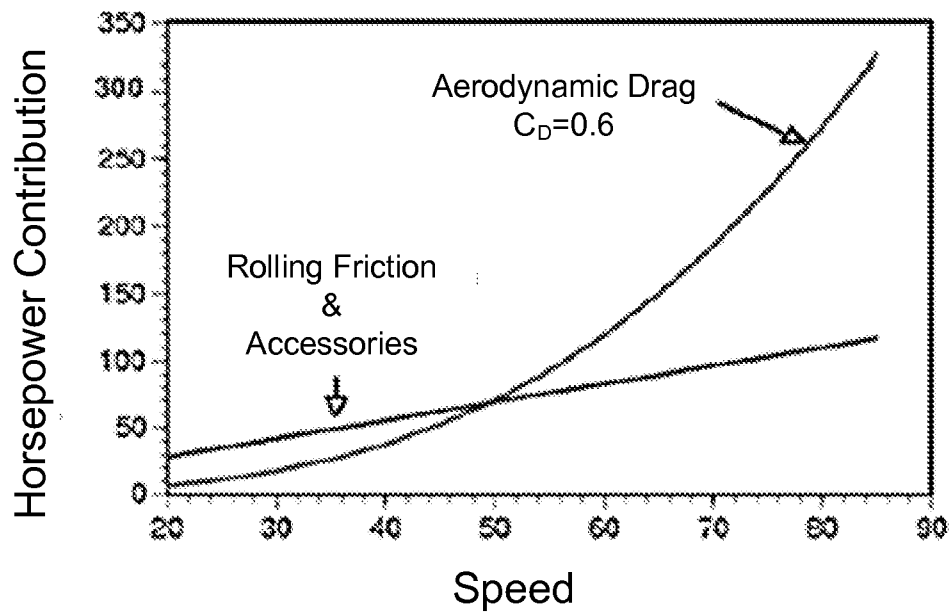
17. A method comprising:
affixing one or more serpentine plasma actuators to a rear surface of a vehicle; and

while the vehicle is in motion, activating the one or more serpentine plasma actuators to inject turbulent structures that are normal to the rear surface of the vehicle,

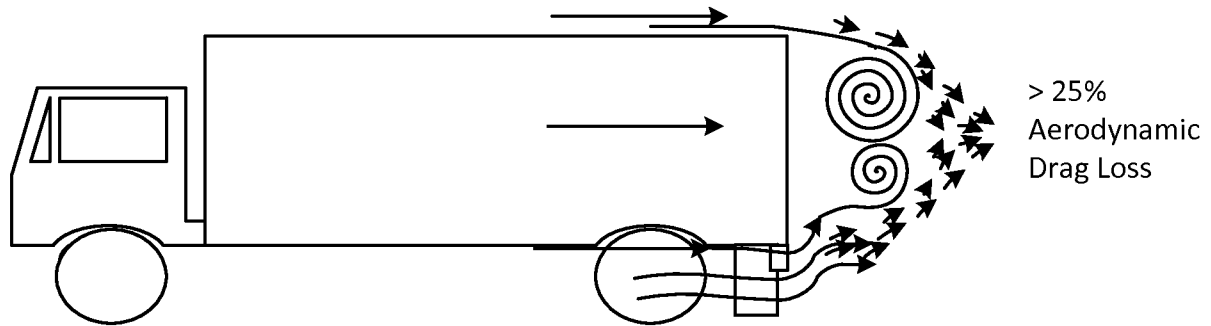
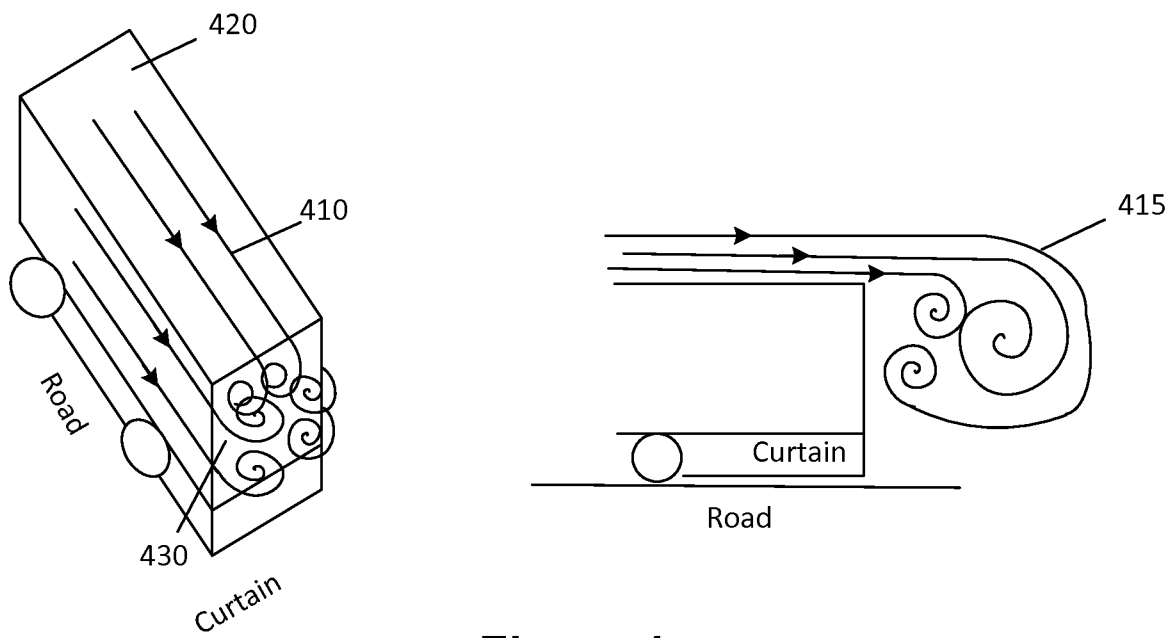
wherein the turbulent structures energize a wake flow of the vehicle creating a high pressure that acts on the rear surface and reduces aerodynamic drag.

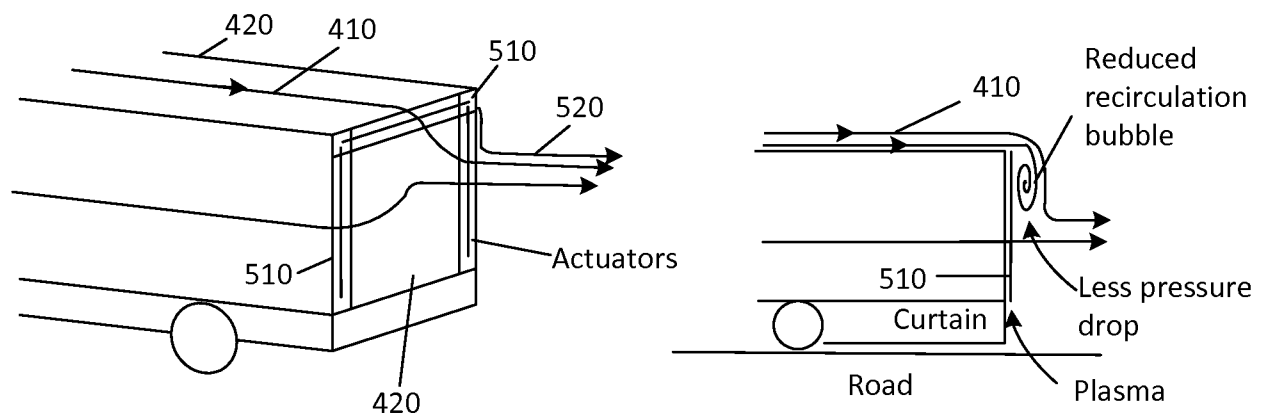
18. The method of claim 17, further comprising:
affixing one or more straight-line plasma actuator channels to the rear surface of the vehicle; and
while the vehicle is in motion, activating the one or more straight-line plasma actuator channels to inject a plasma flow that penetrates a surface flow that has developed on an exterior side of the vehicle and breaks up the surface flow thereby reducing the aerodynamic drag.
19. The method of claim 17, wherein the serpentine plasma actuator is actuated at manual command of an operator of the vehicle.
20. The method of claim 17, wherein the serpentine plasma actuator is automatically actuated upon air speed reaching a designated value.

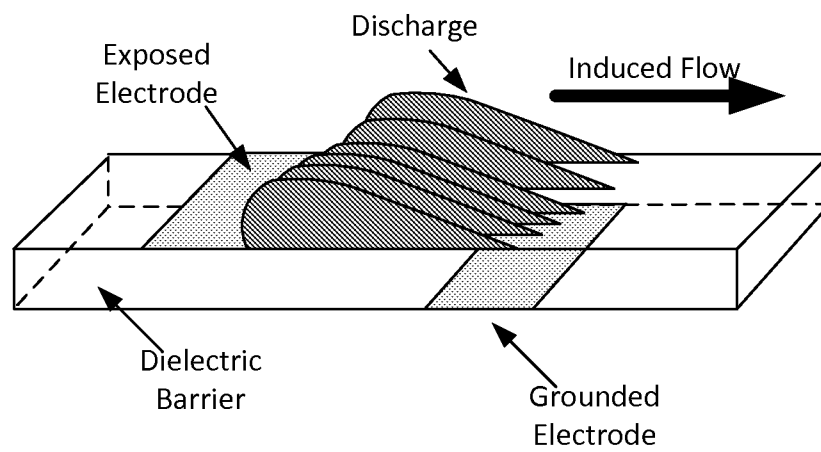
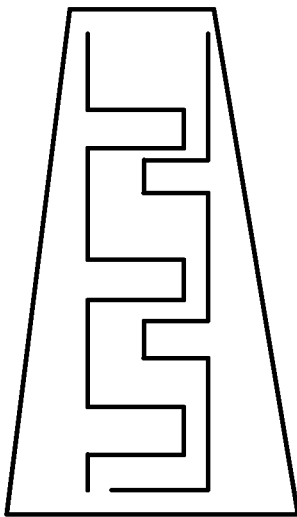
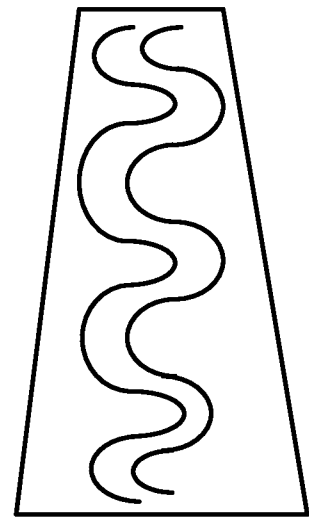
1/14

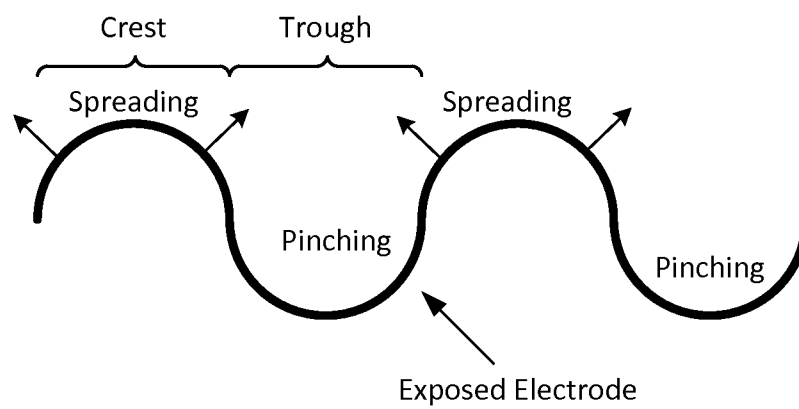
**Figure 1****Figure 2**

2/14

**Figure 3****Figure 4**

**Figure 5**

**Figure 6****Figure 7****Figure 8**

**Figure 9**

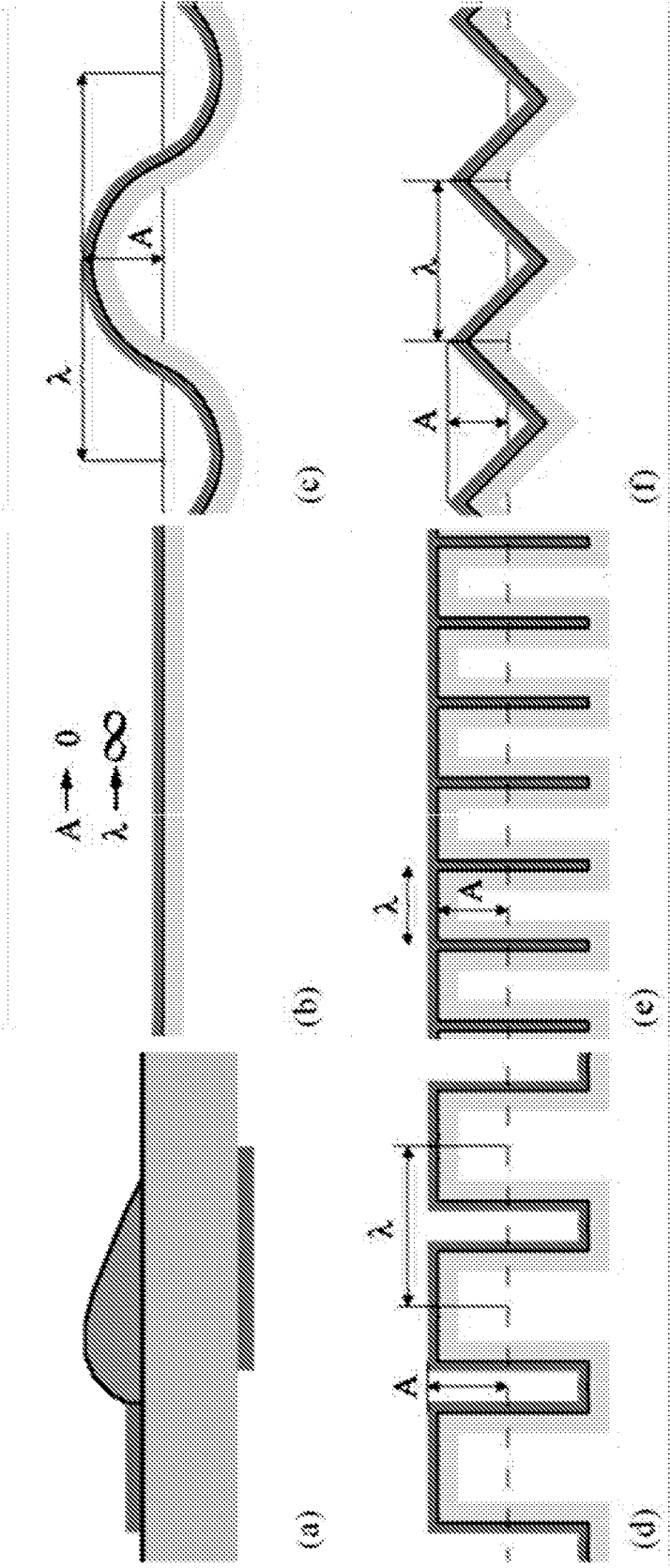


Figure 10

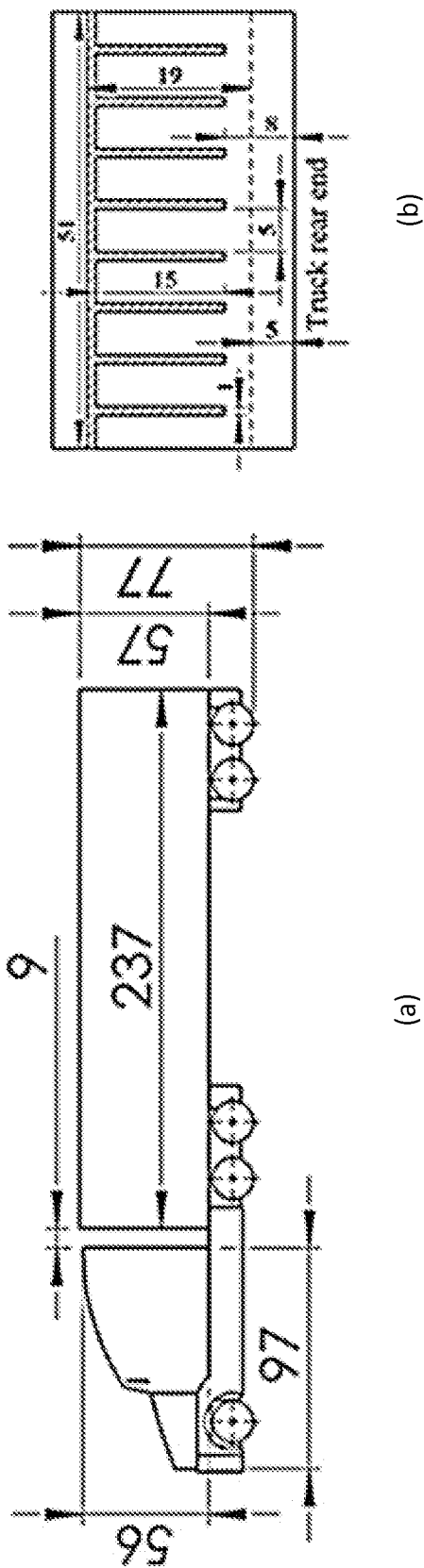


Figure 11

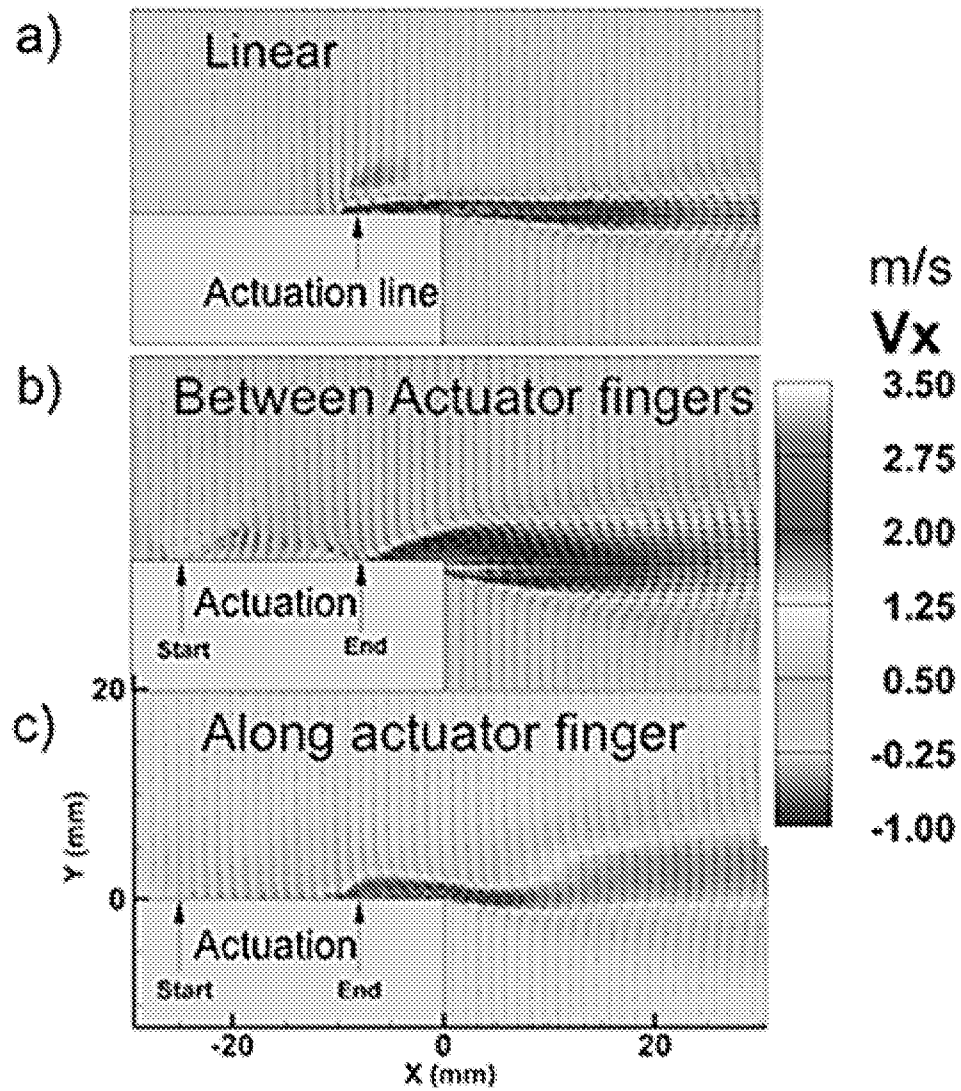


Figure 12

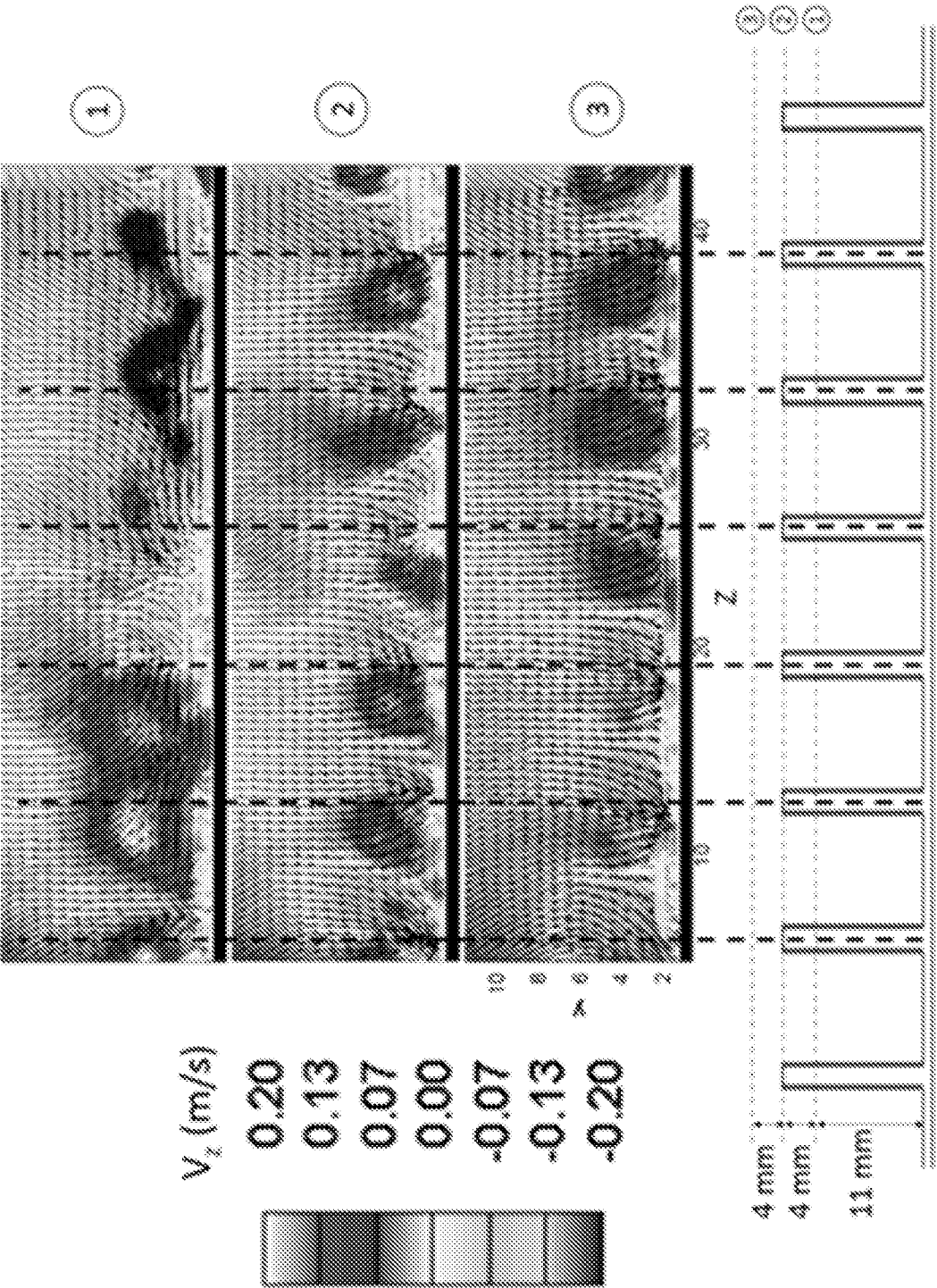
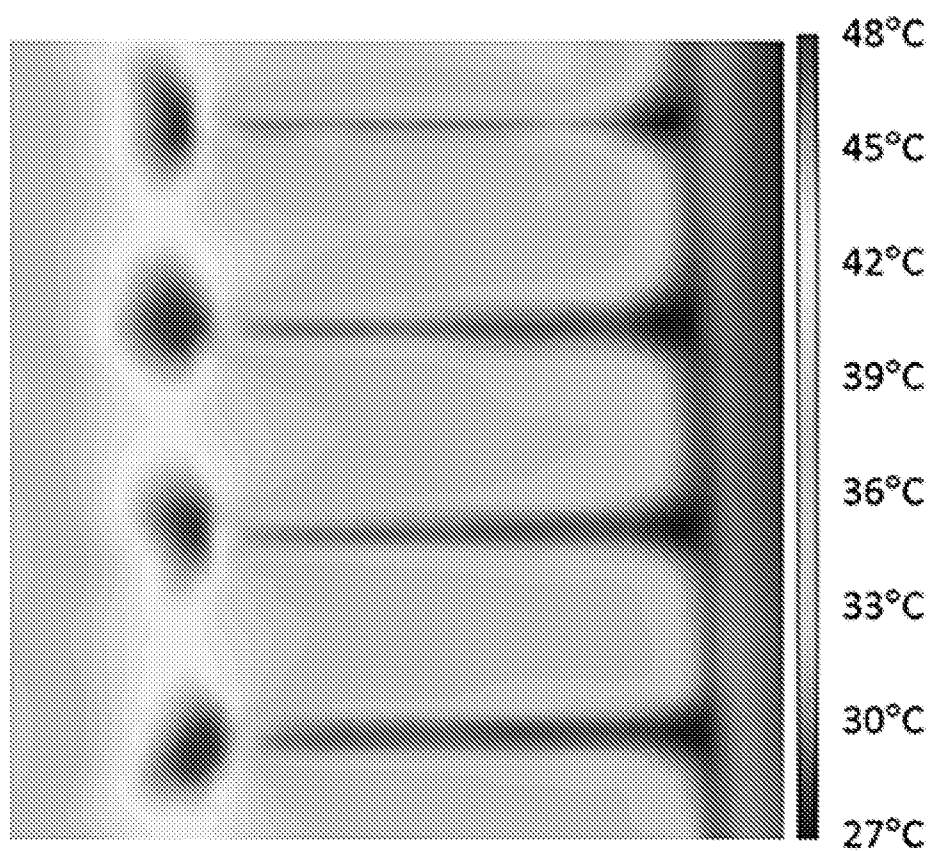


Figure 13

10/14

**Figure 14**

11/14



Figure 15

12/14

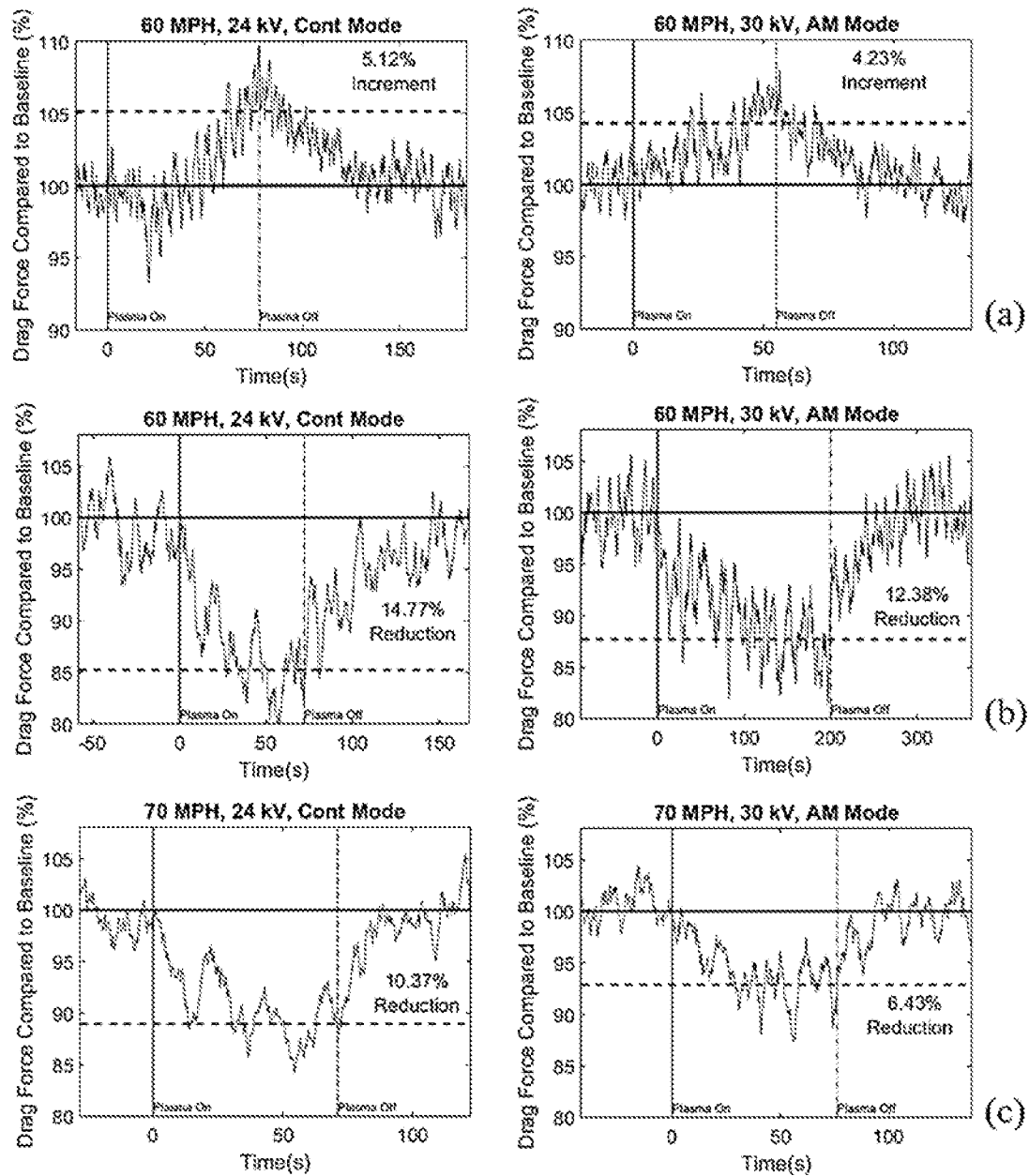


Figure 16

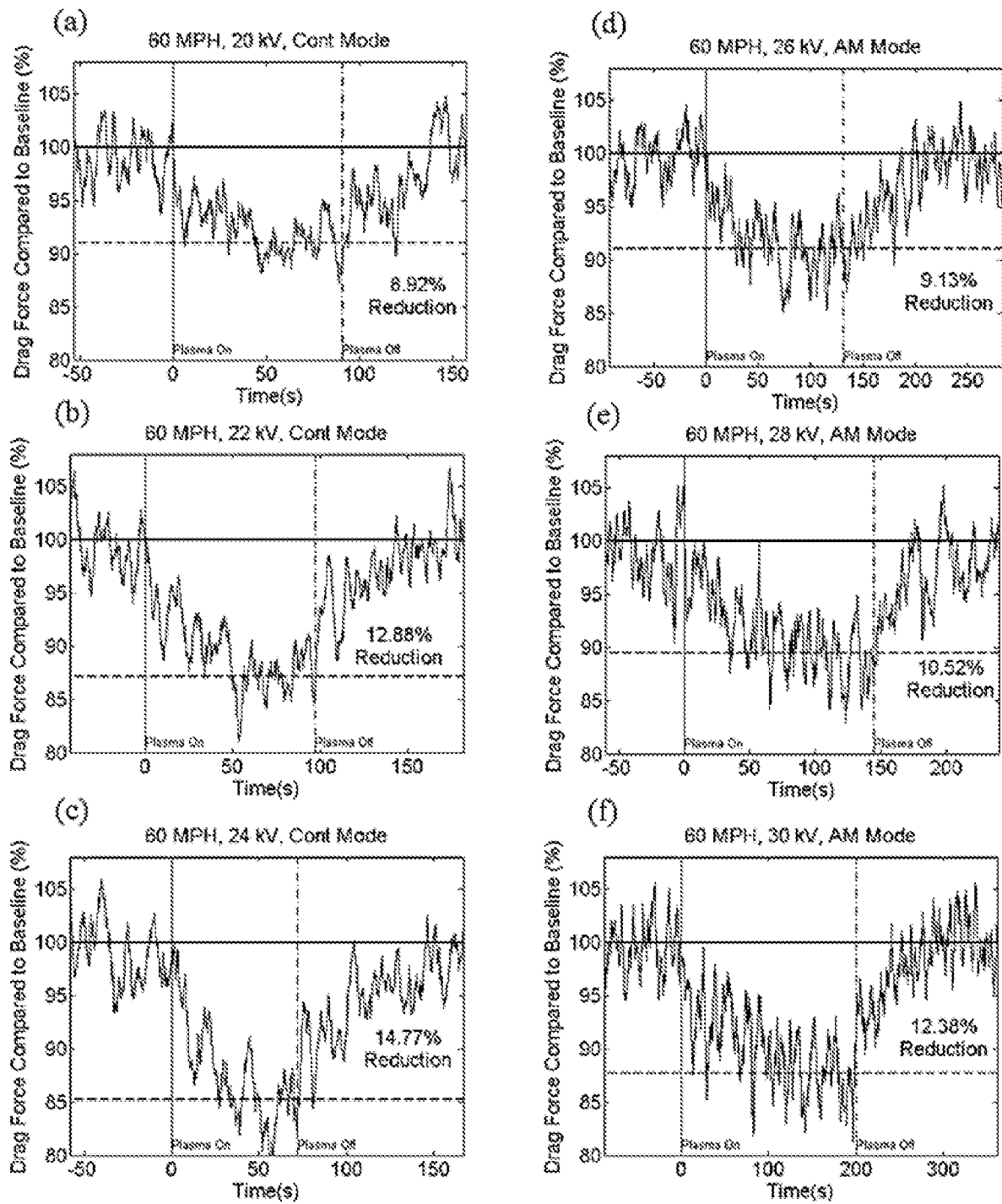


Figure 17

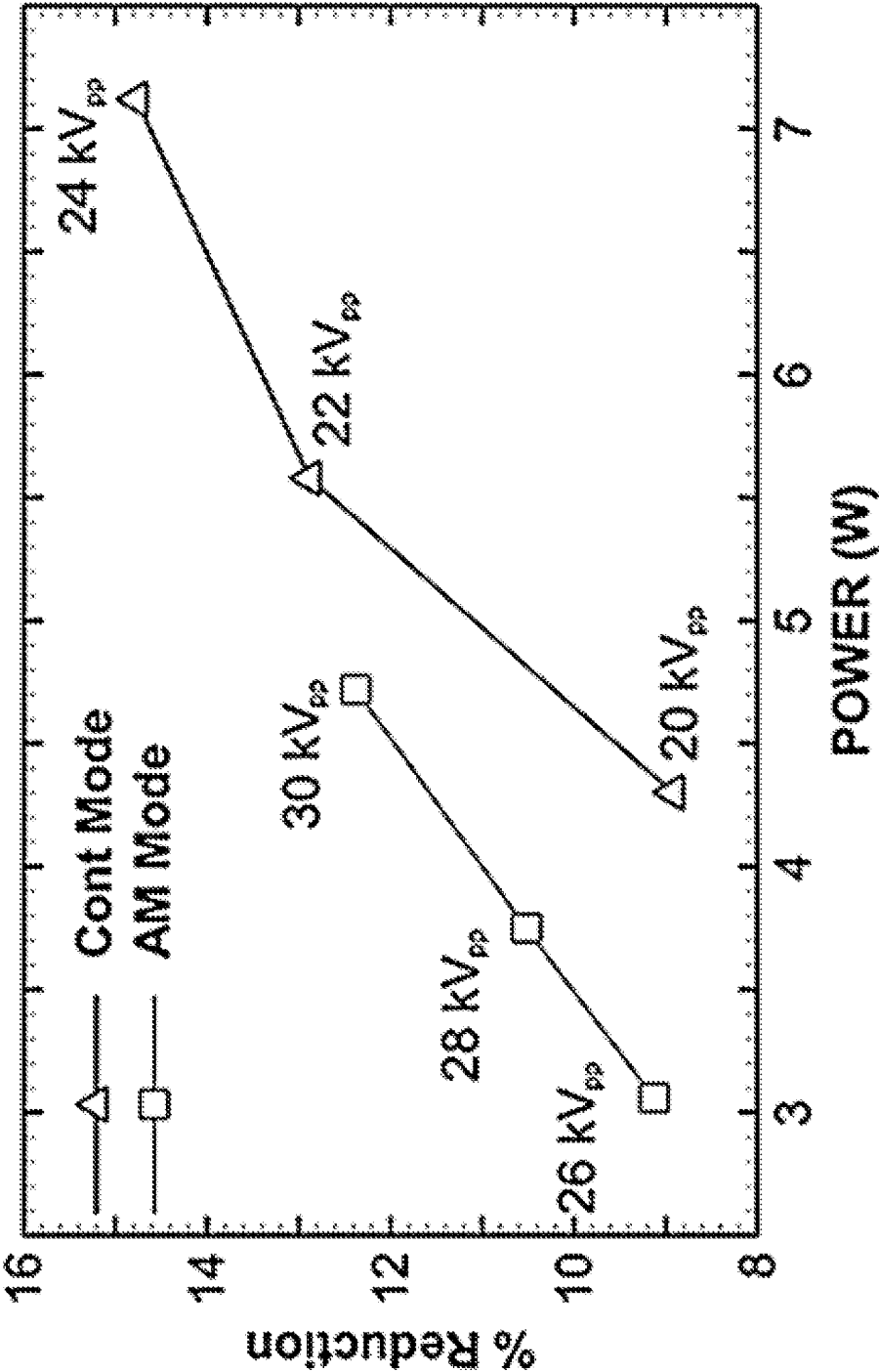


Figure 18